University of Alberta

An Assessment of Open Hole Cavity Completion for Coalbed Methane Reservoirs in La Guajira – Colombia.

By

Yesid Tovar Quimbaya

A thesis submitted to the Faculty of Graduate Studies and Research in Partial Fulfilment of the requirements for the degree of

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To my beloved parents, my lovely wife and my life my son Ricardo José

ABSTRACT

Coalbeds in the San Juan Rancheria Sedimentary basin of Colombia contain many promising coalbed methane reservoirs. These coalbeds currently support active surface mining of coal for power generation.

The project is located in the Cerrejón formation which is a tertiary age sedimentary sequence. The Cerrejón Formation contains more than 70 coal seams, some of them can be traced for 50 kilometers along the entire length of the sedimentary basin. Today, the project has 25 wells in the evaluation stage with encouraging results in some of them. Twenty-four wells have been hydraulically fractured and only one has been openhole completed.

Still major concerns about the coal seams completion techniques arises, in order to find the best way which allow the methane gas to be liberated from the coal matrix. Due to the above, a geomechanic test facility was adapted to accommodate the testing conditions to investigate mechanical rock properties that will permit the understanding of the physical strength of coal seams from the reservoir of interest that could allow to apply a new technique known as openhole cavity completion.

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Additionally, I would like to thank to my friend Jaime Jimenez, who offered insight and encouragement throughout the thesis work, and my advisors Dr. Chalaturnyk and Dr. Polikar.

NOMENCALTURE

A: Sectional cross area

a,s: Hoek and Brown mass rock constants

E: Elastic modulus

C_{3+}: Hydrocarbons with at least three carbons in its chain

m_b: Hoek and Brown constant rock constant

- Greek Letter

σ_1: Principal stress

σ_3: Minor stress, lateral pressure, confining pressure

ε_f: Strain stress

- Abbreviations

API: American Petroleum Institute

BPD: Barrel per day

BWPD: Barrel of water per day

BCF: Billions cubic feet

CBM: Coalbed methane

GIP: Gas in place

GPM: Gallon per minute

GSI: Geological strength index

Mcf/day: Thousand of cubic feet per day

MMCFD: Millions of cubic feet per day

msec/ft: Milliseconds per feet

PPG: Pound per gallon

RPM: Revolutions per minute

SPF: Shot per foot

SPM: Stroke per minute

TCF: Trillion cubic feet

US$/Mcf: US Dollar per thousand of cubic feet

TABLE OF CONTENT

CHAPTER 1 INTRODUCTION	1
1.1 INTRODUCTION	1
1.2 OBJECTIVE	3
1.3 SCOPE	3
1.4 OUTLINE OF THESIS	5
CHAPTER 2 REVIEW OF LITERATURE	7
2.1 COALBED METHANE GENERAL HISTORY	7
2.2 GAS COMPOSITION PRODUCED FROM CBM FIELDS	12
2.3 INITIAL GAS IN PLACE	13
2.4 MAXIMUM GAS RECOVERY FACTOR	13
2.4.1 RESERVES FINDING COSTS FOR COALBED METHANE PLAYS	14
2.5 IDENTIFICATION OF COAL BEDS ON ELECTRICAL LOGS	15
2.6 METHANE PRODUCTION FROM COAL BEDS	17
2.6.1 As Coal Mine Methane	18
2.6.2 Disturbed De-Stressed Coal Seams As Coal Mine Methane	18
2.6.3 Virgin Coal Seams As Coalbed Methane Well	19
2.7 COALBED METHANE EXPLORATION	19
2.8 WELL COMPLETIONS METHODS	21
2.9 COALBED METHANE RESERVOIR SIMULATION	23
2.9.1 Simulator Applications	23
2.10 RESERVOIR SIMULATION IN OPEN HOLE CAVITY PERFORMANCE	24
2.11 IMPLICATIONS FOR OPEN HOLE COMPLETIONS	26
2.12 STATUS OF THE INDUSTRY	27
2.13 GLOBAL OPPORTUNITIES	30

2.14 ENVIRONMENTAL CONSIDERATIONS OF CBM 32
2.15 SAFETY AND ECONOMICS OF CBM PRODUCTION 33
2.16 COALBED METHANE APPLICATIONS 33
CHAPTER 3 GEOLOGY FRAMEWORK 35
3.1 INTRODUCTION 35
3.2 HISTORICAL BACKOUND 36
3.3 REGIONAL GEOLOGY 39
3.3.1 Generalities 39
3.3.2 Regional Stratigraphy 40
3.4 SEDIMENTARY ENVIRONMENTS 42
CHAPTER 4 LA GUAJIRA FIELD HISTORY 43
4.1 INTRODUCTION 43
4.2 DRILLING WELL DESIGN 46
4.3 COMPLETION AND STIMULATION DESIGN 48
4.4 PRODUCTION EQUIPMENT 51
4.5 PRODUCTION DATA 52
4.5.1 Well Guajira – 21 52
4.5.2 Well Guajira – 22 54
4.5.3 Well Guajira – 23 56
4.5.4 Well Guajira – 24 58
4.5.5 Well Guajira – 25 59
4.6 FIELD LA GUAJIRA COMPOSITIONAL GAS ANALYSIS 62
CHAPTER 5 TRIAXIAL TEST RESULTS 64
5.1 INTRODUCTION 64
5.2 TEST OBJECTIVE 65
5.3 ESPECIMEN DESCRIPTION 65
5.4 TEST PROCEDURE 68
5.5 TEST RESULTS 79

5.5.1 Specimen Core – 0 (σ_3= 0 Kpa) 79

5.5.2 Specimen Core – 1 (σ_3= 200 Kpa) 81

5.5.3 Specimen Core – 2 (σ_3= 400 Kpa) 82

5.5.4 Specimen Core – 3 (σ_3= 1000 Kpa) 84

5.5.5 Shear Failure Criterion 86

5.5.5.1 Determination of Hoek and Brown Parameters 89

5.5.5.2 La Guajira Coals 90

5.6 BOREHOLE STABILITY CALCULATIONS TO ASSES OPENHOLE CAVITY COMPLETION PETENTIAL IN LA GUAJIRA FIELD 93

5.7 SUMMARY 99

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS 101

6.1CONCLUSIONS 101

6.1.1 Specimen Considerations 101

6.1.2 Practical Application of the Laboratory Work 102

6.2 RECOMMENDATIONS 103

6.2.1 Samples and Tests 103

6.2.2 Technique Applicability and Future 103

REFERENCES 104

APPENDIX A TRIAXIAL CELL'S CALIBRATION DATA 108

APPENDIX B OPERATION HISTORY IN LA GUAJIRA FIELD 114

LIST OF TABLES

Table 2-1 Gas Composition From Two Basins	12
Table 2-2 Costs During CBM Exploration	15
Table 2-3 Well Log Response in Coal and Host Strata	16
Table 4-1 Hole and Casing Size	47
Table 4-2 Drill String and Bottom – Hole Assembly	47
Table 4-3 Production Casing Cement Design	48
Table 4-4 Fracture Job Design	49
Table 4-5 Breakdown Design	50
Table 4-6 Fracture Schedule Design	50
Table 4-7 Production Equipment	51
Table 4-8 Gas Composition Results from La Guajira Field	63
Table 5-1 Proximate Test Results from La Guajira Coal Seams	65
Table 5-2 Core Specification from La Guajira Field	66
Table 5-3 Peak Strength of Moura Coal Mine Samples	89
Table 5-4 Strength Parameters from La Guajira Field Coal	91
Table 5-5 Stress Results for La Guajira Field Cores	92
Table 5-6 Mohr and Coulomb Terms Converted Fom Hoek and Brown Terms	94
Table 5-7 Fracture Data	94
Table 5-8 La Guajira – 21 Well Data	95
Table 5-9 Sensitivity Parameters for STABView® Analyses	96

LIST OF FIGURES

Figure 2-1 Coalification Process	8
Figure 2-2 Coal Rank	9
Figure 2-3 Sandstone – Conventional Vs. Coal Unconventional Reservoir	10
Figure 2-4 Production Methods for Coal Mine Methane	17
Figure 2-5 CBM Exploration Model	20
Figure 2-6 Coventional Vs. CBM Well	21
Figure 3-1 Project Location	36
Figure 3-2 Regional Geological Stratigraphic Column	41
Figure 3-3 Sedimentary Environments	42
Figure 4-1 Well Guajira No. 21 Production History	53
Figure 4-2 Well Guajira No. 22 Production History	55
Figure 4-3 Well Guajira No. 23 Production History	57
Figure 4-4 Well Guajira No. 24 Production History	58
Figure 4-5 Well Guajira No. 25 Production History	61
Figure 5-1 Core Conserved at Low Temperature	67
Figure 5-2 Rough Core from La Guajira Field	69
Figure 5-3 Core Finished Ready to Test	70
Figure 5-4 Membrane to Cover the Core	71
Figure 5-5 Core Installed in Triaxial Test Base	72
Figure 5-6 Cell Assembling Top Cup	73
Figure 5-7 Triaxial Cell With Top Cup	74
Figure 5-8 Cell Installed in its Base and Lined Up With Accessories	75
Figure 5-9 Core Sheared Still Inside the Membrane	77

Figure 5-10 Core Sheared 78

Figure 5-11 Core- 0 Sheared 80

Figure 5-12 Core – 0 at 0 kPa Confining Pressure 80

Figure 5-13 Core-1 Sheared Core-2 Sheared 81

Figure 5-14 Core-1 at 200 kPa Confining Pressure 82

Figure 5-15 Core – 2 Sheared 83

Figure 5-16 Core-2 at 400 kPa Confining Pressure 84

Figure 5-17 Core – 3 Sheared Core-1 85

Figure 5-18 Core-3 at 1.000 kPa Confining Pressure 85

Figure 5-19 Hoek and Brown Parameters for La Guajira Field Coal 91

Figure 5-20 Comparison of Computed Hoek and Brown Failure Envelope with Experimental Data 92

Figure 5-21 Laboratory Data Run at Different Normal stresses 95

Figure 5-22 Simulation Results with a Cohesion of 0.1 97

Figure 5-23 Simulation Results with a Cohesion of 1 98

Figure 5-24 Simulation Results with a Cohesion of 2 99

Figure A-1 Cell-1 Strain Sensor Calibration Data 109

Figure A-2 Cell-2 Strain Sensor Calibration Data 110

Figure A-3 Pore Pressure Sensor Calibration Data 111

Figure A-4 Load Cell Sensor Calibration Data 112

Figure A-5 Differential Pressure Transducer Sensor Calibration Data 113

Figure B-1 Well Schematic "Guajira No. 21" 116

Figure B-2 Well Schematic "Guajira No. 22" 118

Figure B-3 Well Schematic "Guajira No. 23" 121

Figure B-4 Well Schematic "Guajira No. 24" 124

Figure B-5 Well Schematic "Guajira No. 25" 126

CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

Colombia is one of the largest countries in South America with a population of approximately 40 million of people. It possesses many attractive coal deposits distributed throughout the country. These coal seams range from low to high rank, and have been extensively explored and produced in the northern part of the country, especially along the border with Venezuela.

Evaluation of the coal deposits in this northern region began in 1865, and focused on defining the Cerrejón Formation, which remains the best coal deposit in Colombia. In 1970, a government agency named "Ingeominas" conducted a reserve calculation and determined that there were 112 million tonnes of proved reserves and 138 million tonnes of probable reserves in 20 coal seams with excellent properties for thermal use. More studies and exploration has been done and today, within the central part of the Cerrejón Formation, the proven reserves are estimated to be 225 million tonnes. These are currently being exploited using open pit mining techniques.

In 1994, exploration began for evaluating the possibility of coalbed methane production in the Cerrejón Central area. Three core holes were drilled to determine the best coal seams, regarding gas content. Initial development began in 1997, and ended in 1998. The wells were stimulated by hydraulic fracturing, and initial well testing and production over the last several years has yielded encouraging results.

The coalbed methane project is an association contract with ECOPETROL (Empresa Colombiana de Petroleos), Colombia's National Oil Company. As a component of the development phase, the present research was undertaken to evaluate the possibility of using openhole cavity completion techniques to further stimulate coalbed methane production. This technique involves the enlargement of the productive zone by surging the interval with a mix of water and air in such a way that the natural cleats of the coal seams improve their connectivity far beyond the borehole, thereby helping to create a less tortuous path for the liberated gas from the coal surface.

1.2 OBJECTIVE

The objective of this research is to evaluate the potential of open hole completion techniques as a replacement for hydraulic fracture stimulation, in order to apply it in coalbed methane reservoirs in the northern part of Colombia. Substantial coalbed methane resources exist in Colombia and their economical exploitation will require the application of current coalbed methane production practices, such as open hole cavity completions.

Effective implementation of open hole cavity completion techniques requires an understanding of the mechanical properties of the coal. A second objective of this research is to evaluate the rock properties of core samples obtained from the coalbeds of the Cerrejón Formation.

1.3 SCOPE

Coalbed methane exploration and development is a complex field, and presents many challenges over conventional natural gas production. The application of openhole cavity completions within a commercial development would involve a myriad of issues from surface equipment to produced water disposal and personnel safety. It is not the intent of this research to explore these aspects of openhole cavity completion

techniques. Rather, the scope of this work is to collect and synthesize all pertinent information on the coalbeds of the Cerrejón Formation. Based upon a review of previous experience with openhole cavity completions, the relevance of this technique to coalbed methane production in Colombia will be discussed.

Well schematics were prepared for each well in order to give a better understanding of the coal seams distribution as well as the magnitude of the operation carried out during the stimulation practices.

The laboratory work was planned with specimens from the local mine, that would represent as closely as possible the coal seams explored in the coalbed methane wells. The open hole cavity completion success relies on the operational design work that incorporates the strength of the seams that must be overcome in order to create the cavity. In order to understand how the coals of the Cerrejón Formation compare to coals where open hole cavity completions were utilized, it is necessary to develop some basic mechanical rock properties. Strength tests on coal specimens obtained from the Cerrejón Formation will be conducted while it is understood that defining other coal characteristics such as permeability, or fracture density are also important in the application of open hole cavity completion. These are, however, not included in the scope of this thesis.

1.4 OUTLINE OF THESIS

Chapter 1 provides an introduction to the concept of coalbed methane (CBM) production, and a history of its development in Colombia. The objective and scope of the research are also described in Chapter 1.

Chapter 2 presents an overview of the coalbed methane reservoirs from the genesis process of the methane gas to the relevant geological issues of CBM exploration, and to stimulation and completion techniques. A brief introduction to rock mechanics theory utilized in characterizing the stress – strain behavior of the coals is provided, followed by an overview of CBM production worldwide.

Chapter 3 provides background information on the local and regional geology within Colombia. The focus is the origin and geologic structures that contain the coalbeds.

Chapter 4 discusses the current status of the field, and describes the drilling, completion and stimulation operations in each well. As well, daily methane gas and water production data for each well are provided along with produced gas quality data. Owing to the sensitive commercial nature of some aspects of the project, it has not been possible to include hydraulic fracturing performance.

Chapter 5 describes the laboratory triaxial tests, carried out on the coal samples from La Guajira field. La Guajira is the province in Colombia where the project is located. The data on the rock strength of the coal seams provide critical information for evaluating the opportunity of applying openhole cavity completion in this particular coalbed methane reservoir in the northern part of Colombia.

Chapter 6 summarizes the findings in the thesis and provides conclusions on the potential for openhole cavity completions. This chapter also includes some recommendations regarding additional research that could help evaluate coalbed methane production in Colombia.

CHAPTER 2 REVIEW OF LITERATURE

2.1 COALBED METHANE GENERAL HISTORY

Coalbed methane is the technical term given to methane gas held in coal seams. It is released or produced when the hydraulic pressure within the buried coal is reduced by pumping fluids to reduce reservoir pressures. The methane is predominantly formed during the coalification process (Figure 2.1). Organic matter is slowly transformed into coal due to temperature and pressure increases as the organic matter is buried deeper by additional deposits of organic and inorganic matter over long periods of geological time. This is referred to as thermogenic coalbed methane.

More often, specially in lower rank and thermally immature coals, recent bacterial processes, involving naturally occurring bacteria associated with meteoric water recharge at outcrop or subcrop, can dominate the generation of coalbed methane. This is referred to as late stage biogenic coalbed methane. Figure 2.2 shows the coal ranking.

During the coalification process, a range of chemical reactions take place, which produce substantial quantities of gas. While much of this gas escapes into the overlying or underlying rock, a large amount is retained within the forming coal seams. However, unlike conventional natural gas reservoirs, where gas is trapped in the pores or void spaces of a rock,

methane formed and trapped in coal is actually adsorbed onto the coal grain surfaces or micropores, and held in place by reservoir (hydraulic) pressure. Therefore, because the micropore surface area is very large, coal can potentially hold significantly more methane per unit volume than most conventional reservoirs (Figure 2.3).

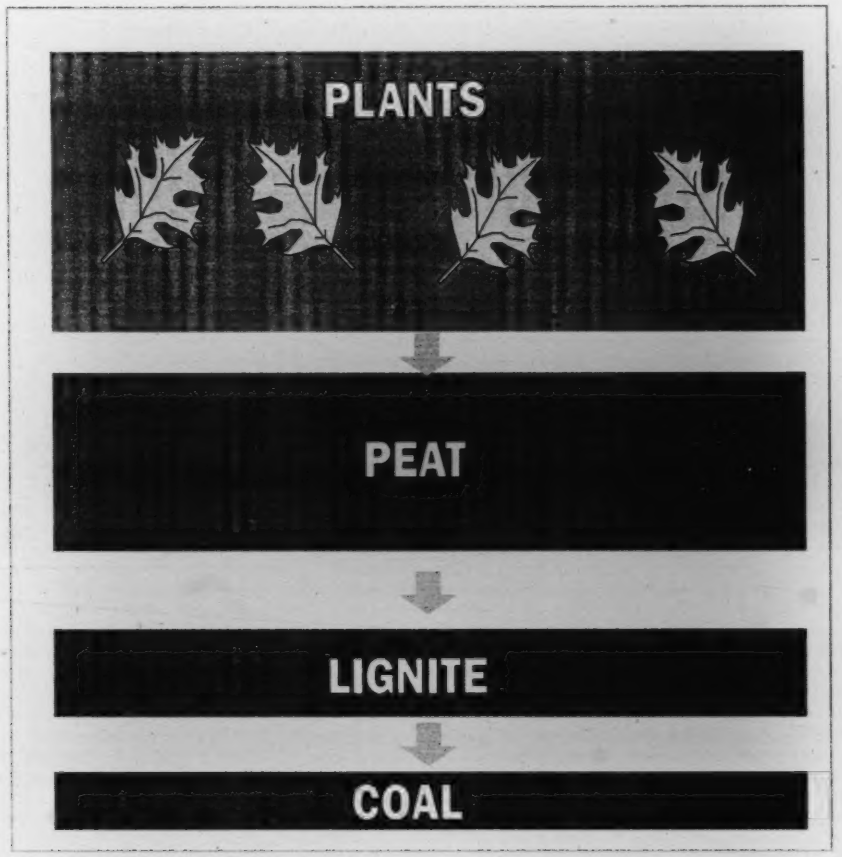

Figure 2.1 Coalification Process

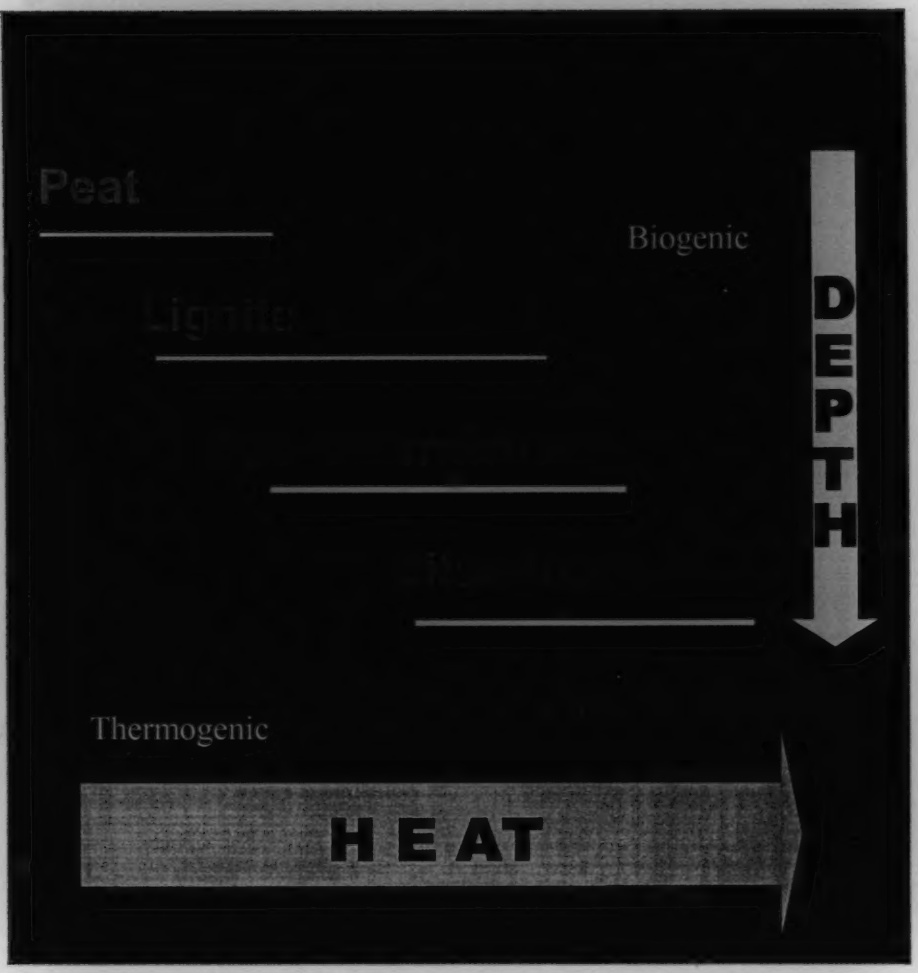

Figure 2.2 Coal Rank.

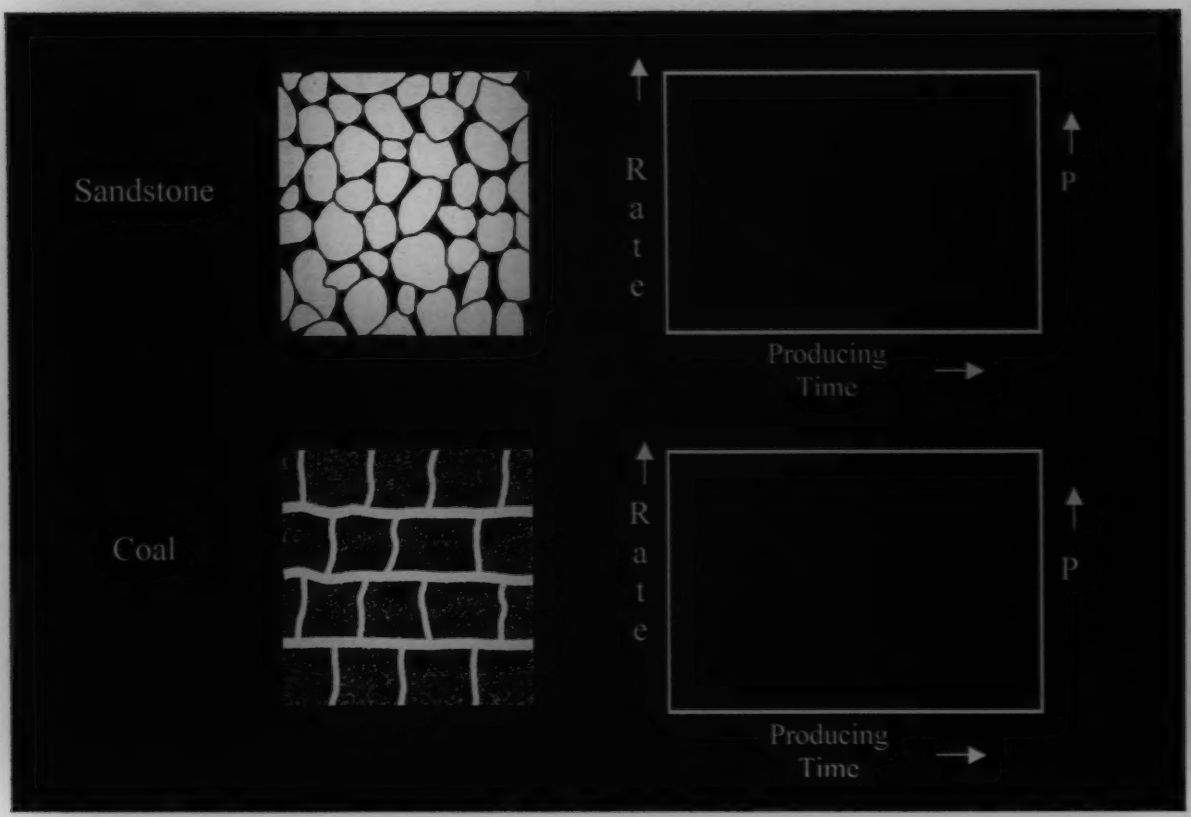

Figure 2.3 Sandstone – Conventional Vs. Coal Unconventional Reservoir

The presence of gas in coal seams has been a major threat to safety in underground coal mining since the beginning of that industry. As a coal face is exposed in a mine, the pressure differential between the body of the coal seam and the open face in the mine causes adsorbed gas in the coal to leak from the vicinity of the open face into the mine atmosphere, frequently creating an explosive mixture of air and methane.

Mining practices were developed to meet this safety problem with gas drainage holes, initially being drilled from the coal face into the seam, and later by the use of vertical holes being drilled from the surface into the coal seam ahead of the mined face.

Progressively, the extracted gas was used at and around the mine for its energy value. Then, as the degassing techniques improved and volumes of gas extracted per hole increased, an industry producing gas in a similar manner to other natural gas reservoirs was born.

For the industry to progress, however, a body of technical expertise and knowledge had to be developed. It became important to understand which coals were likely to have higher gas contents, which type of geological structural settings preserved the best internal fracture, and which drilling, stimulation and completion techniques worked best in different geological and structural settings.

Gas derived from coal is generally pure and requires little or no processing because it is solely methane and not mixed with heavier hydrocarbons, such as ethane, which is often present in conventional natural gas. This particular characteristic is remarkably present in the composition of the gas produced from La Guajira Field. Coalbed methane has a slightly higher energy value than some natural gases.

Coalbed methane is generally produced from relatively shallow wells (200 to 1,000 metres), which are cheaper than conventional natural gas wells. However, gas pressures at wellhead are lower, thereby increasing the cost of gathering and transport.

2.2 GAS COMPOSITION PRODUCED FROM COALBED METHANE FIELDS

Gas produced from coal seams is higher in methane than gas produced from conventional reservoirs. Ethane and heavier hydrocarbons are more strongly adsorbed than methane, consequently, they may not be released or desorbed in the first stage of production. Gas analysis performed at different fields can differ from each other in the methane content and in thermal power. Table 2.1 shows data from two coalbed methane fields.

Component	Warrior Basin (mole %)	Piceance basin (mole %)
Methane	96.20	90.25
Ethane	0.01	2.66
Carbon Dioxide	0.10	6.38
Nitrogen	3.40	0.00
Hydrogen	0.01	0.00
Helium	0.26	0.00
C_{3+}	0.71	0.71
Thermal Power (BTU/scf)	978	N/A

Table 2.1 Gas Composition From Two Basins (from Scott, 2001b)

Coalbed gas is generally of high quality, suitable for direct delivery into natural gas pipelines

2.3 INITIAL GAS IN PLACE

The magnitude of the amount of initial gas-in-place is one of the key reservoir parameters that influences the gas production and the producible reserve potential of coalbed gas reservoirs. This reservoir parameter is intrinsically difficult to determine accurately. In many established coalbed methane plays, the cumulative gas produced has exceeded the estimated initial gas-in-place. This has happened in many coalbed methane reservoirs in the San Juan and Powder River basins. This underestimation indicates that the reservoir parameters used to calculate the initial gas-in-place values were inaccurate, and that significant potential may exist for larger reserves in many existing fields (Hill, 2001b).

2.4 MAXIMUM GAS RECOVERY FACTOR

It is widely accepted that the recovery factor from a coalbed methane reservoir is in the range of about 50 to 70% of initial gas – in – place. The magnitude of the recovery factor is somewhat lower than that of conventional gas reservoirs, but is an inherent feature of the pressure depletion recovery method that is used worldwide for production of

coalbed methane. This production technique includes continuous water removal from the resource, thereby progressively reducing the reservoir pressure, which results in the desorption of the sorbed gas phase.

Today, many new techniques that will improve the recovery of the commodity are being evaluated. These look at the factors that will accelerate the gas production rate and overcome the recovery factor limitations of the pressure depletion method. In the future, these enhanced recovery methods may also enable commercial exploitation of coalbed methane reservoirs that cannot be economically produced using pressure depletion techniques.

2.4.1 RESERVES FINDING COSTS FOR COALBED METHANE PLAY

Table 2.2 gives an estimate of the real costs involved in coalbed methane exploitation for several basins. These figures reflects the true cost of drilling and completion operations in seven basins in the USA. Exploration costs, reserves and recovery factor are very sensitive factor during the evaluation of a coalbed methane project.

Basin	Drainage Area	GIP – Recovery Factor	Max. Well Prod. Rate	Well Drilling and Completion	Reserve Finding Cost
	Acres	Fraction	Mcf/day	US$	US$/Mcf
Northern San Juan	160	0.70	2000	750,000	0.11
Piaceance	40	0.15	140	834,000	1.23
Greater Green River	160	0.60	240	750,000	0.36
Raton	160	0.55	300	330,000	0.18
Uinta	160	0.50	692	400,000	0.25
Powder River	120	0.50	250	65,000	0.21
Upper Texas Gulf Coast	160	0.70	1000	435,000	0.28

Table 2.2 Costs During Coalbed Methane Exploitation (Scott, 20001a)

2.5 IDENTIFICATION OF COAL BEDS ON ELECTRICAL LOGS

Accurate identification of coal seams using electrical logs is very critical for the interpretation of coal depositional patterns and coal seam geometry. Some logs, such as density, neutron and sonic logs, are very special in identifying coal, whereas other logs, such as gamma ray and resistivity,

must be used in combination with others for an accurate interpretation (Scott, 2001b).

Table 2.3 gives some typical well log responses in coal and host strata.

Well Log	Units	Coal	Shale	Sandstone	Limestone
Gamma-ray	**API**	0-20	80-140	10-30	5-10
Sonic	**msec/ft**	110-170	70-150	65	62
Neutron	**F(%)**	>50	25-60	3	10
Density	**g/cm^3**	1.3-1.8	2.2-2.75	2.48	2.5

Table 2.3 Well-Log Response in Coal and Host Strata (Scott, 2001b)

The operational definitions of coal are based more on art than on science. They are based on calibrating geophysical log responses with drillers logs, cuttings and cores, and on knowledge of stratrigraphic occurrence of coal and observation of subtle log responses such as curve shape and peakness. The combination of all the concepts above, when used properly, will result in an appropriate interpretation and definition of coalbeds.

2.6 METHANE PRODUCTION FROM COALBEDS

Coalbed methane occurs naturally in coal seams. It is a clean burning fuel with properties similar to those of natural gas. Unlike natural gas, however, coalbed methane is found at comparatively low pressures, making the fuel particularly suitable for industrial purposes. Figure 2.4 shows the different methods for methane production from coal mines.

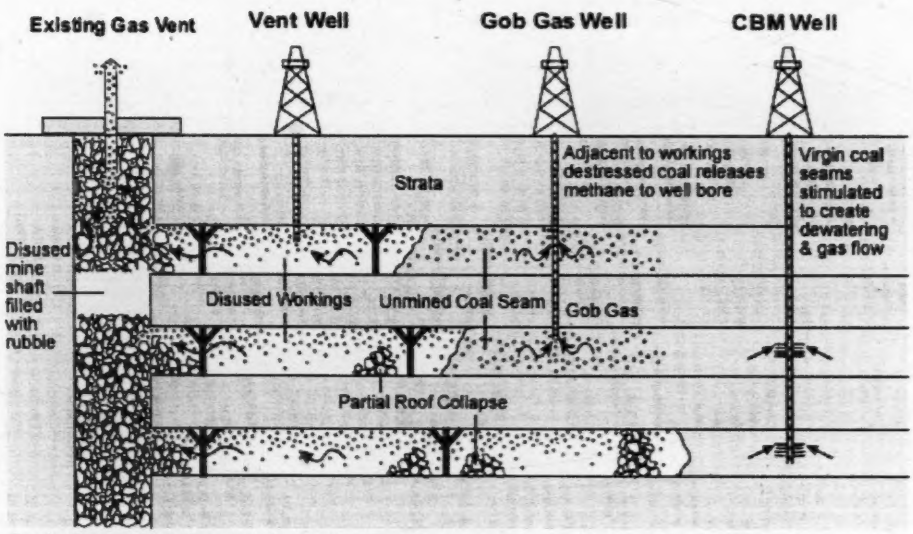
Existing Gas Vent
Vent Well
Gob Gas Well
CBM Well
Strata
Adjacent to workings destressed coal releases methane to well bore
Virgin coal seams stimulated to create dewatering & gas flow
Disused mine shaft filled with rubble
Disused Workings
Unmined Coal Seam
Gob Gas
Partial Roof Collapse
Production methods for coalmine methane

Figure 2.4 Production methods for coal mine methane (from Garrat, 2002).

In many countries, the coal mining industry has been producing large quantities of methane as an unwanted hazard since the beginning of the 18th century. Some coal-based industries use methane from the coalfields

to provide fuel for their activities, for generating electricity and for third party sales to other industrial entities.

There are three principal situations in which methane from coal occurs. Each one requires a different production technique as indicated below.

2.6.1 As Coal Mine Methane

The methane is a waste product from previous mining activity. At the end of a mine's commercial use, shafts are usually filled with rubble and capped with concrete. Naturally occurring coal mine methane migrates to these shafts from the exploited coal seams and surrounding rock strata. Vents are installed through the concrete cap to reduce the risks associated with the build up of this gas. Some of these vents emit gas of commercial quantity, which can then be captured by gas gathering systems. Additional quantities of methane can be produced through the drilling of additional boreholes into the abandoned mine, as shown in Figure 2.4.

2.6.2 Disturbed And De-Stressed Coal Seams As Coal Mine Methane

The methane is a waste product of mining adjacent to previous mining activity where the pressure of the coal seams is reduced by the proximity of the workings. Flowing relatively freely through channels to the wellbore, the gas, known as "gob gas", can be released and utilized through the drilling of conventional wells, as shown in Figure 2.4.

2.6.3 Virgin Coal Seams As Coalbed Methane Well

The methane gas is held under pressure in undisturbed coals, often in strata saturated by water. In these circumstances, production usually requires the drilling of wells. Stimulation of these wells is required, and may be achieved by fracturing the coals and improving their permeability near the wellbore. Alternatively, cavities can be created in the coal seams. In either case, water is produced first. This reduces the reservoir pressure and allows the gas to flow into the wellbore at commercial quantities of 150 - 800 Mcf/d/well. Production from such wells can be sustained in some cases for more than 30 years.

2.7 COALBED METHANE EXPLORATION

Geologic and hydrologic controls are critical parameters for coalbed methane producibility. A dynamic interaction among these controls and their spatial relations governs the production of the commodity. Figure 2.5 shows the main geologic and hydrologic controls that interact in a successful coalbed methane exploration model.

Coalbed methane exploration strategies are often based only on the location having the greatest net coal thickness, and ignore other hydrogeologic and geologic factors affecting coalbed methane

producibility. Coalbed methane producibility is determined by the complex interplay among six critical controls: depositional settings and coal distribution, coal rank, gas content, permeability, hydrodynamics, and tectonic and structural setting, as shown in Figure 2.5

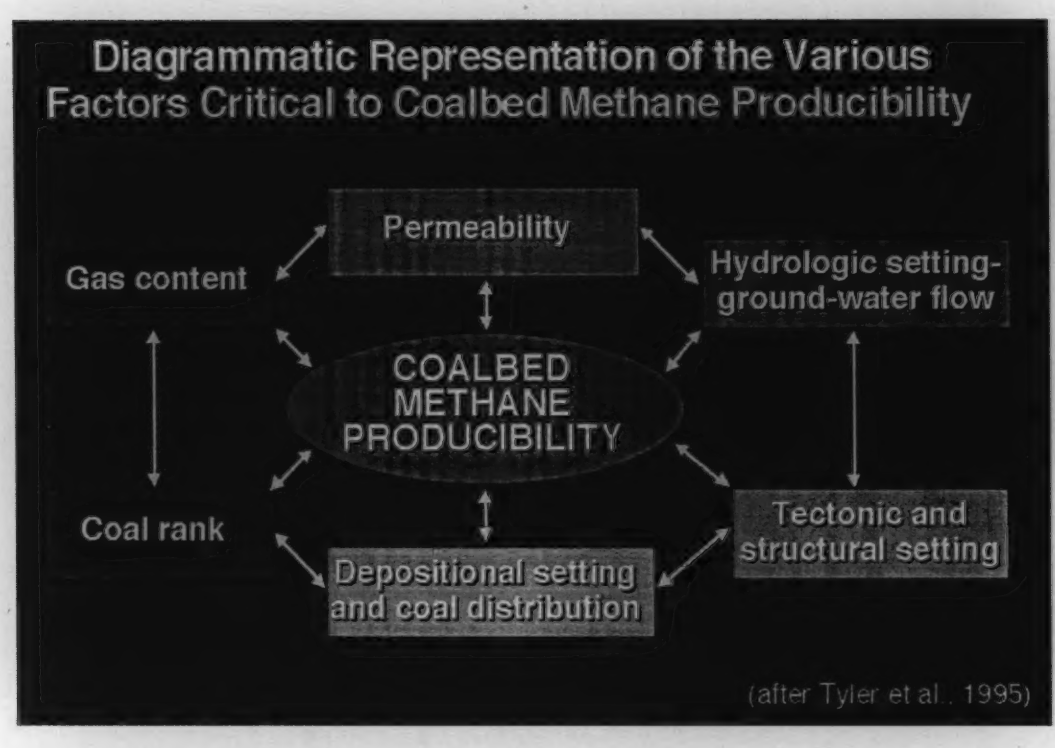
Diagrammatic Representation of the Various Factors Critical to Coalbed Methane Producibility
Permeability
Gas content
Hydrologic setting-ground-water flow
COALBED METHANE PRODUCIBILITY
Coal rank
Tectonic and structural setting
Depositional setting and coal distribution
(after Tyler et al., 1995)

Figure 2.5 Coalbed Methane Exploration Model (from Bachu, 2001).

The potential for higher coalbed methane producibility will be reduced If one or more of these key hydrogeologic factors is missing (Scott, 2001a).

2.8 WELL COMPLETION METHODS

Coalbed methane wells have been completed using a technology similar to that of conventional gas wells, with some changes in order to adjust the flow path of the gas liberated from the coal seams. The parameter which governs the methane gas produced from a coal seam is desorption of the gas from the coal matrix. Figure 2.6 shows the differences between conventional and coalbed methane wells.

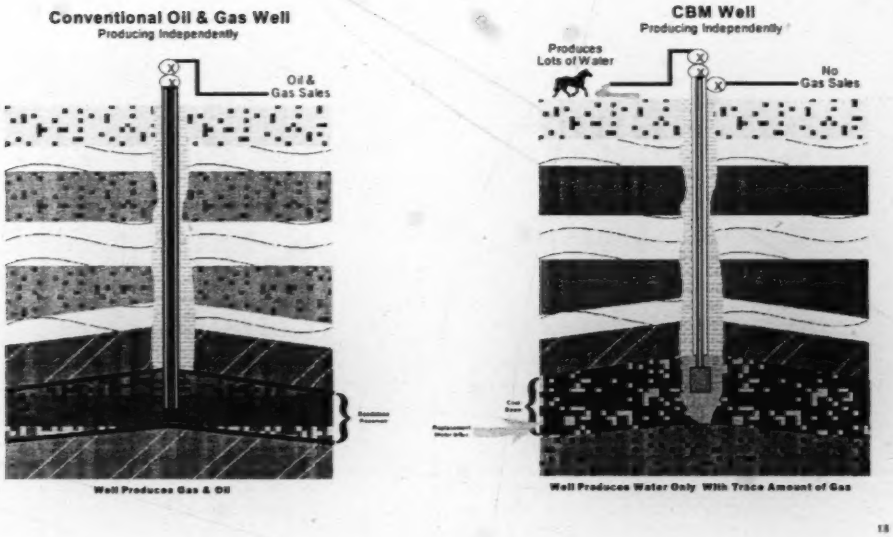

Figure 2.6 Conventional versus coalbed methane well (from Fadness,2001).

The completion process includes many alternatives, which depend on the formation type, and the coal sensitivity to chemical products during drilling

or stimulation operations. Before producing the reservoir, it is necessary to decide the type of formation access desired, whether openhole, cased hole, perforating or hydrojetting. If any of these configurations leads to non-commercial production, it is important to plan a stimulation job, such as borehole enlargement by underreaming or hydrojetting, cavitating or hydraulic fracturing. The success or failure of the technique used is based on the reservoir capacity and characteristics. The production stage involves the conduit or tubing, the artificial lift system used to dewater the seam, scale problems, gas quality and stress sensitivity. These factors will act in favor or against the degree of damage done to the coal.

The most extensively used production techniques are hydraulic fracturing and open hole cavity completion. The hydraulic fracturing applied to coal seams accelerates the desorption mechanism by allowing greater pressure reduction within the reservoir which initiates greater gas desorption. Hydraulic fracturing attempts to link effectively natural fractures in the coal seam with the wellbore while avoiding near wellbore formation damage. Openhole cavity completion is the result of enlarging an openhole interval. This wellbore enlargement is performed by injecting air or an air/water mixture into an openhole interval at high pressure, and suddenly releasing the wellbore pressure. The sudden release of the wellbore pressure causes friable, low strength coal and rock particles to

slough into the wellbore. The injection/blow down sequences are repeated until wellbore stabilization is achieved.

2.9 COALBED METHANE RESERVOIR SIMULATION

Coal gas reservoirs are extremely complex, both in terms of geology and production mechanism. Unlike conventional gas reservoirs, the traditional methods of analogy, decline curve analysis and material balance are not adequate to describe two –phase (water-gas) flow conditions in naturally fractured coal reservoirs. However, reservoir simulation provides a consistent and reliable way to account for the mechanisms of coal seam gas desorption and diffusion. A reservoir simulator also provides the means by which field and laboratory data can be integrated into a single geologic/reservoir model in order to cost effectively evaluate exploration protocols and long-term development strategies (Palmer et al., 1995).

2.9.1 Simulator applications

- Gas rate forecasting can be used to determine the economical recovery range for a field or per well.
- Completion strategies can be optimized to maximize economic gas recovery.

- Well spacing designs can be improved for long term development plan strategies.
- Diagnosis of production problems can identify wells which are performing below potential, and provide the basis for the design of optimum remediation treatments.
- Location of infill wells can be determined by identifying areas of the reservoir with high potential.
- Laboratory test data can be validated.
- Weaknesses in critical reservoir data can be identified, and the production sensitivity to many parameters can be evaluated.

2.10 RESERVOIR SIMULATION IN OPEN HOLE CAVITY WELL PERFORMANCE

Open hole cavity completions have provided a significant improvement in production in various basins producing methane gas from coal seams, where the reservoir characteristics are appropriate for cavitation to be applied. For the wells completed in open hole cavity, the gas production rates exceed the amount of gas from those completed using hydraulic stimulation techniques, often by a factor of 3 to 10 times. In many cases, simulation analysis of cavity-completed wells has been undertaken to better understand the downhole conditions responsible for this success,

and to determine how these conditions differ from those of fracture-stimulated wells.

The well test analysis and the history matching of field rates and bottom hole pressures using a coal seam gas simulator show that cavitation appears to have created a zone of enhanced permeability in the near wellbore region, which results in a great improvement in production. Good matches between simulated and observed well performance were obtained with an enhanced permeability zone of 250 md for a radial distance of 130 ft from the cavitated well, in the Black Nest field. Beyond the enhanced zone, the formation permeability remained unchanged at 25 md, which represents the average of the well test values. The history matching also yielded a face cleat to butt cleat permeability ratio of 1.5 to 1 , which is in agreement with the well test analysis (Levine , 1996).

Sensitivity simulations have been performed to better understand the great increase in production of wells completed in open hole cavity compared to those which were hydraulically fractured. Hydraulic damage induced fractures appear to explain the increase in production for the cavitated wells, as is the case when the reservoir is quite uniform.

2.11 IMPLICATIONS FOR OPEN HOLE COMPLETIONS

Openhole cavity completion technique has evolved greatly since the first coalbed methane well was drilled in the San Juan Basin back in the 1950s. A cavity is a consequence of wellbore instability, and is analogous, at least in part, to the wellbore instability problems with sand flow – back in unconsolidated sand. The permeability surrounding a cavity appears to be enhanced by tensile fracture induced during air/water injection phases, and shear failure zones induced during blow-down stages of the cavitation process. Many studies have been conducted to improve the borehole stability and to understand the true impact of mechanical rock properties on the success of creating an optimum cavity. As well, a lot of evaluations have been made to compare the performance between the different completion techniques, especially hydraulic fracturing and open hole cavity. Extensive evaluations have also been made to see the applicability and performance of some traditional devices used in conventional oil and gas operations. Some changes were required to adapt these for improving this technique. They include under reamers to enlarge hole diameter and remove skin effect during drilling, sloted liners to prevent open hole cavity collapse, jetting tools to enhance the cavity diameter, simulation programs to improve the cavitation understanding without drilling a single well, and well testing to evaluate formation damage or enhancement. All of the above have the common objective to

provide an effective link to the reservoir in order to achieve economic gas production rates.

Different economic evaluations have presented the openhole cavity completion technique as an alternative stimulation method that is much more attractive in terms of production and costs. The cost of a hydraulic fracture of a well could represent 40 to 60% of the total cost of the well, and in many cases, the production rate of a well in open hole cavity completion is two to three times higher than that of one stimulated with hydraulic fracture (Scott,2001a).

In short, the openhole cavity completion technique has implications that have impacted positively the coalbed methane industry not only economically but also operationally, and in scientific studies of reservoir characterization and bore hole stability applications.

2.12 STATUS OF THE INDUSTRY

While CBM exploration and appraisal operations are ongoing in many of the major coal basins around the world, the vast majority of commercial production is still in the U.S. Originating in the Black Warrior Basin of Alabama, and followed by prolific production from the San Juan Basin of Colorado / New Mexico, coalbed methane currently accounts for 7% or 1.3

trillion cubic feet (TCF) of total annual natural gas production in the U.S (Scott, 2001b). By mid-1999, more than 8,000 coalbed methane wells were reported to be in production, representing a great growth from a negligible production base in the mid-1980's.

Gas deliverability from most Warrior Basin wells is modest, with large quantities of accompanying water, which adds to operating costs. Production rates in the San Juan Basin have been substantial, some 4 to 5 times higher than in the Warrior Basin, with some wells achieving as high as 20 million cubic feet per day (MMCFD), with rates of 10 MMCFD not being uncommon.

Attention is now being directed towards other basins in the Rocky Mountain foreland, such as the Raton, Green River, and Powder River Basins. In Canada, coalbed methane exploration activity is been started by different companies but not much information has been released yet at this early stage.

CBM resource appraisal, drilling and production testing are presently underway in at least a dozen other countries, and the proportion of non-US production can be expected to soar during the next 10 years. China, the world's largest coal producer, has generated particular interest. Its CBM resources are estimated to range from between 1,000 and 2,800 TCF, many times larger than its conventional gas potential. Chinese coal mine operations already extract gas from within the underground mines.

In 1990, 110 mines recovered 15 billion cubic feet (BCF) of coalbed methane. Although modest, this production has demonstrated the viability of the resource to the Chinese authorities. As a result, a number of areas are been exploited as joint ventures with foreign companies, with initial drilling showing promising results.

India's coalbed methane resource potential has been estimated at 280 TCF, again far surpassing its conventional gas endowment. Partnerships between U.S. and Indian companies are presently drilling and evaluating several large CBM exploration permits. On the basis of initial investigations, Bangladesh, too, is regarded as having the potential to produce moderate to large volumes of coalbed methane in close proximity to major markets.

Drilling success in Zimbabwe has demonstrated the prospect of commercial coalbed methane development in this country.

In several parts of Eastern Europe, a number of coalbed methane ventures involving foreign investment and application of U.S. technologies are reported to have met with mixed success. Production tests in some regions are said to favor commercial production, which is anticipated once negotiations with regulatory authorities have been resolved.

The tempo of coalbed methane exploration has increased significantly in Australia since the entry of major international coalbed methane producers

and the involvement of major local utility companies. These activities are supported by a major research effort, modifying U. S. technologies to suit local conditions.

2.13 GLOBAL OPPORTUNITIES

The growth of the U.S. coalbed methane industry has stimulated some petroleum companies to identify other regions of the world with similar geological characteristics, along with attractive regulatory, marketing, and gas pricing regimes. Lowell Petroleum was among the first foreign companies to recognize China's coalbed methane potential, and has also identified opportunities in Zimbabwe, India, Bangladesh, the Philippines, Eastern Europe and Australia.

Coalbed methane resources are roughly commensurate with reserves of bituminous coal, so that regions such as Colombia, Canada, China, India, the former states of the CIS, Eastern Europe and Australia are particularly well-endowed. Some of these countries have adequate supplies of conventional gas or are otherwise unattractive for coalbed methane ventures, whereas others present unique opportunities. China and India, for example, produce limited volumes of conventional gas and are plagued by severe pollution problems from coal-fired power generators. Coalbed methane has the potential to service local energy needs and to complement coal in electricity generation, particularly to accommodate demand surges.

China presents a unique opportunity. The particular relevance of coalbed methane to China is illustrated by the fact that, of the country's 2,288 large underground coal mines, 53 percent have severe problems with excess methane. Underground methane gas explosions are responsible for exceptionally high human mortality, and this hazard is increasing as mining necessarily extends to progressively greater depths. Consequently, the need to extract coalbed methane in China is driven by two factors: the safety problems arising from a requirement to produce coal at higher rates from deeper mines, and the shortfall in conventional gas supply to many regions.

Opportunities in some small countries arise from a complete absence of conventional gas (for example in parts of sub-Saharan Africa), or as a result of rapid industrial growth outpacing the collective availability of domestic energy resources (in parts of south east Asia). Some companies have been involved in coalbed methane appraisal in southern Africa for a number of years, and have identified Zimbabwe and South Africa as holding particular promise. The Philippines is another country, in Asia, where petroleum companies have a well-developed network of technical contacts that have assisted in the identification of coalbed methane targets.

Similarly, coalbed methane opportunities have been brought to the oil industry's attention in Namibia, Botswana, Zambia, Mozambique, North

Korea, Taiwan, Great Britain, Spain, Poland, the Ukraine and the Czech Republic. Some of these potential ventures have been rejected on the basis of technical or fiscal considerations, whilst others offer the appropriate mix of geological and regulatory ingredients.

2.14 ENVIRONMENTAL CONSIDERATIONS OF CBM

There exists the potential for a reduction in the creation of greenhouse gases by the use of CBM in the generation of electricity. Consider the following issues:

- Carbon dioxide emissions per unit of electricity generated are typically in the order of 1,180 tonnes per GWh for brown coal, 25 tonnes per GWh for black coal, and 600 tonnes per GWh for coalbed methane.
- Coalbed methane is free of sulphur, and does not generate sulphur oxides (a source of both pollution and acid rains when it is burned).
- Methane itself is a greenhouse gas if allowed to vent. It is estimated that coal mining operations within the former CIS states alone emit between 0.6 and 1.0 BCF of methane into the atmosphere every day.
- Methane gas is a greenhouse gas 21 times as potent as carbon dioxide. Avoiding its release to the atmosphere can contribute greatly to protection of the global enviroment.

- Preventing one billion cubic feet of methane emissions is equivalent to planting 120,000 acres of trees or eliminating the emissions from 89,000 automobiles in one year.

2.15 SAFETY AND ECONOMICS OF COALBED METHANE PRODUCTION

- The safety of underground coal mining is greatly improved by in seam or surface gas drainage operations.
- Faster mining rates are possible in degassed coals, resulting in lower production costs.
- Degassing of the coal enables deeper mining to be achieved, therefore increasing reserve size.

2.16 COALBED METHANE APPLICATIONS

- Commercial and industrial: heating greenhouses, co-firing methane in coal-fired industrial and utility boilers, enriching medium-quality gas for pipeline injection.
- Developing technologies: power generation using micro-turbines or very low–emission fuel cells, methanol production, supplemental fuel for blast furnaces, small – scale liquefied natural gas production, brine water treatment.

- Ventilation air methane: supplement primary fuels in power generations or boilers/furnaces, heat recovery using thermal oxidizers and catalytic processes.

- Mine – site uses: facility water and ventilation air heating.

CHAPTER 3 GEOLOGICAL FRAMEWORK

3.1. INTRODUCTION

This chapter reviews the geological features of the coalbed methane basin area. This project is located in a methane concession in La Guajira, in the northern part of Colombia, covering over 240,000 acres, with gas – in - place estimated at 3 TCF. The original concession, granted on April 14, 1994, consisted of 2,471,000 acres, with the exclusive right of exploiting the coalbed gas resources in the Cesar-Rancheria Valley. The area was reduced to the most prospective 180,000 acres in October 1994. The retained acreage covers the primary areas of CBM potential within the valley, with coalbeds underlying essentially the entire 180,000 acres.

The basin being evaluated is named " Rio Rancheria Basin". For more than 20 years, this valley has been a world-recognized large-scale open pit source of export quality thermal coal. The sequences of coal are in a continuous geological trend called " el Cerrejón", with a mining area bigger than 37,000 acres within the basin. The Cerrejón Formation is mined into three basic zones, each named Cerrejón North, Cerrejón Central and Cerrejón South respectively. The coalbed methane project is located specifically in the Cerrejón Central zone. These zones are exploited by the Colombian government, Exxon and Carbones del Cerrejón, with an

approximate annual production of 20 million tonnes of low ash thermal coal for the US and European power markets. Figure 3.1 shows the geographic location of the project, as indicated by the flag.

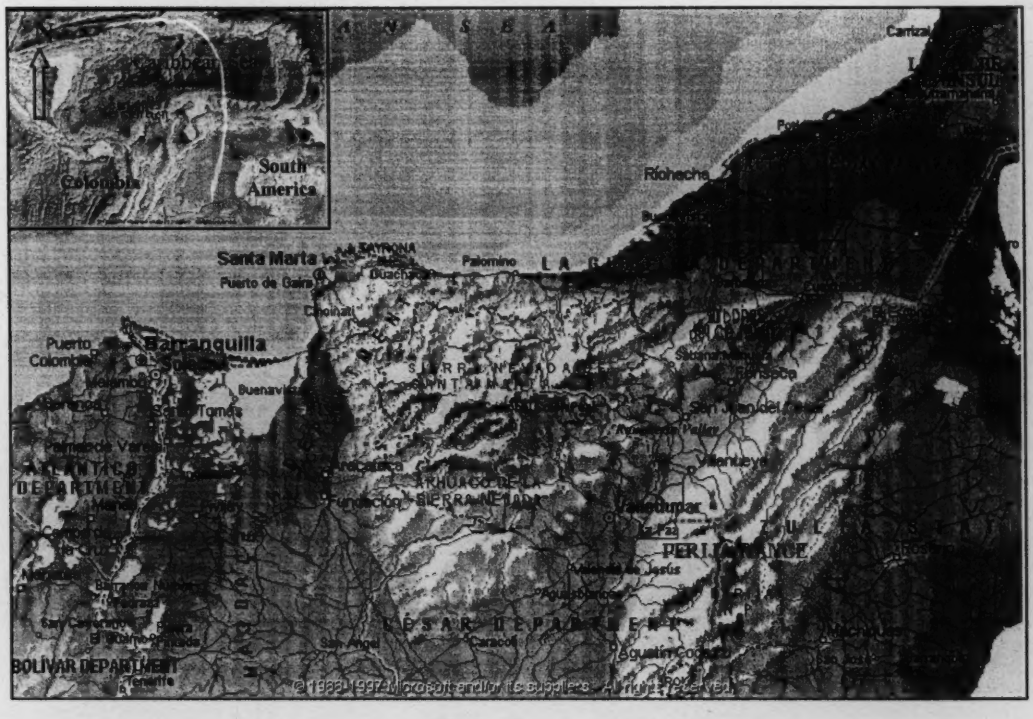

Figure 3.1 Project Location

3.2 HISTORICAL BACKGROUND OF THE BASIN

The exploration history of the development of the Cerrejón basin is given below.

- 1870: "Coal Mines of Valledupar", a document written by John May, is apparently the first report about coal deposits of " El Cerrejón".

- 1880: William Fleig, the US Minister of Mines, visits La Guajira with a group of American geologists and engineers.

- 1894: A French group reportedly carries out the first real study, although very little is known of the work beyond reports of the sinking of prospect inclines.

- 1942: The Tropical Oil Company drills 9 boreholes in the Cerrejón Anticline, and as above, very little is known about the work done.

- 1946: The Colombian Government, under the auspices of the "Instituto de Fomento Industrial" (IFI) commissions an exploration campaign, which is eventually carried out between 1952 and 1954. Several seams are prospected by means of trenches, inclines and shallow pits. One hundred and fifty rotary air blasts are drilled down to depths of 430 feet. Records from this program are not available.

- 1969 to 1972: IFI contracts a South African company, Mining & Engineering Technical Services, to do some limited drilling and testing in the Cerrejón Central area. Field work and logistics are

supplied by Ingeominas, the Colombian equivalent of the Geological Survey. Around 40 boreholes are drilled, and the Ingeominas geologists do extensive surface mapping at various scales.

- 1972: Exploraciones Colombianas SA (ExCol) marks the start of the recent exploration history of the coal deposit in the Cerrejón Central.

- 1976: The state coal company, Carbocol, becomes directly involved in the exploration development of the Cerrejón field. IFI, Ingeominas, Cerrejón Carboneras, Ecopetrol and Colminas, all transfer their various rights and responsibilities for the development and exploration of the field to Carbocol. Carbocol continues to have all exploration and development rights over all coal resources in the Rancheria Valley.

- 1994: The Colombian Government decides to split off the rights to all coal resources in the Cerrejón field not tied to the Cerrejón Central to a new state company called Ecocarbón

- 1998: Ecocarbón is amalgamated with Colminas to form MinerCol, the current manager of all non-petroleum mineral interests on behalf of the Colombian government.

3.3 REGIONAL GEOLOGY

The following summary of regional geology is taken from actual studies recorded in "Ministerio de Minas" Colombia. The Cerrejón Formation is a tertiary age sedimentary sequence, which contains up to 70 coal seams, in relatively non deformed sedimentary sequences. The Cerrejón deposit has been subjected to extensive, penetrative deformation during the Andean crustal-scale collision.

3.3.1 Generalities

The Carbones del Cerrejón coal deposit is contained in a southeasterly dipping sequence of Paleocene-age sediments that are themselves contained within extensive, crustal-scale thrust slices that have a crudely similar southeasterly dip to the sediments themselves.

The economic coal sequence is contained within the Cerrejón Formation, a pro-grading, deltaic succession of sandstones, siltstones, mudstones and claystones. Deposition of peat was extensive and many of the economic seams have impressive extents. Some of the main seams can

be traced or correlated for 50 kilometers along the entire length of the Rancheria Valley. The coal sequence exposed, and being mined in Venezuela across the Perijá Mountains, is widely believed to be the exact same succession.

3.3.2 Regional stratigraphy

The stratigraphy of the area of Cerrejón Central shows a progression from much older rocks in the north-west, in the Sierra Nevada basement, to the youngest, overlying the coal succession, exposed just below the Cerrejón Thrust, on the southeastern edge of the Rancheria Valley. Further to the southeast, across the Sierra de Perijá, almost the entire stratigraphy is repeated in a series of north-westward verging thrust slices and recumbent folds.

Figure 3.2 shows a regional geological stratigraphic column. The Cerrejón Formation is Upper Paleocene in age. The major rock types are sandstones, siltstones, coal and claystones, in order of abundance. The sandstones constitute 38% of the stratigraphic section, the siltstones 33%, coal 14%, and the claystones 8%.

The minor rock types, which individually constitute less than 1.5% of the stratigraphic column, consist of shale, schist and limestone. The above information has been gathered from the core wells drilled in the area.

Coal seams, varying in thickness from tenths of inches to more than 22 meters, are found in 770 meters of this sequence. The lower portion, roughly 185 meters thick, is devoid of any coal. The total, true thickness of the Cerrejón Formation is about 1,692 meters.

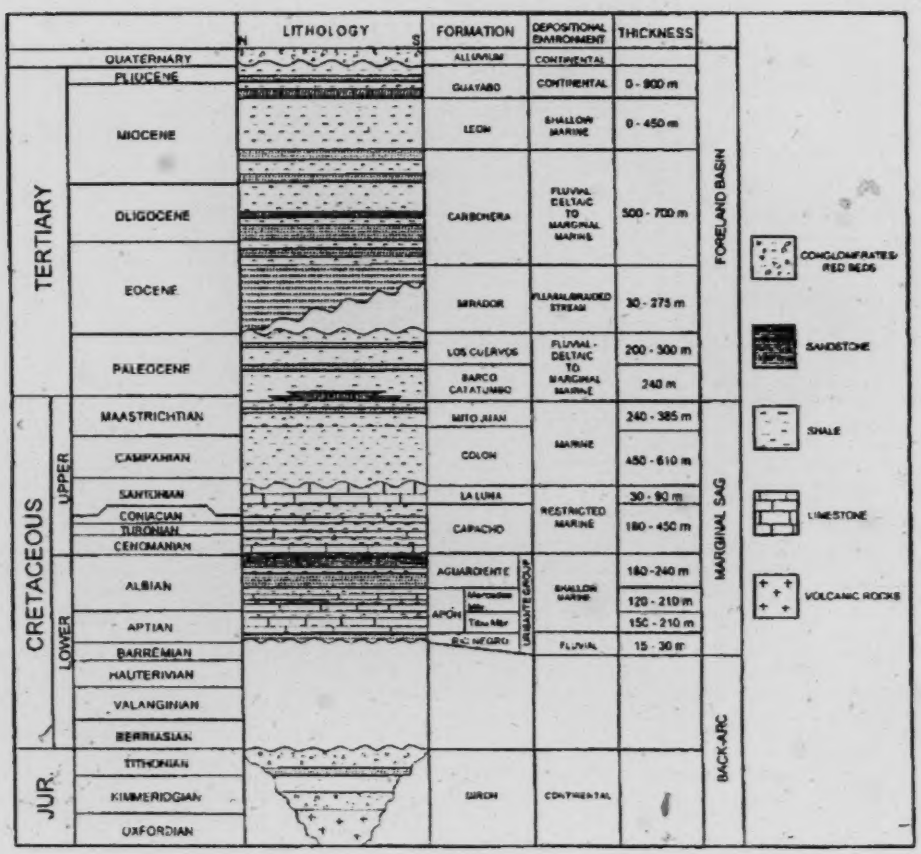

Figure 3.2 Regional Geological Stratigraphic Column

3.4 SEDIMENTARY ENVIROMENTS

The depositional systems, typical sedimentary structures and facies sequences anticipated to have played a role in the Cerrejón coal deposit are explained in this section. The depositional processes that were active within the wider Magdalena basin are described to highlight the importance of sedimentological observations in the understanding of the formation of coal deposits such as the Cerrejón, as shown in Figure 3.3.

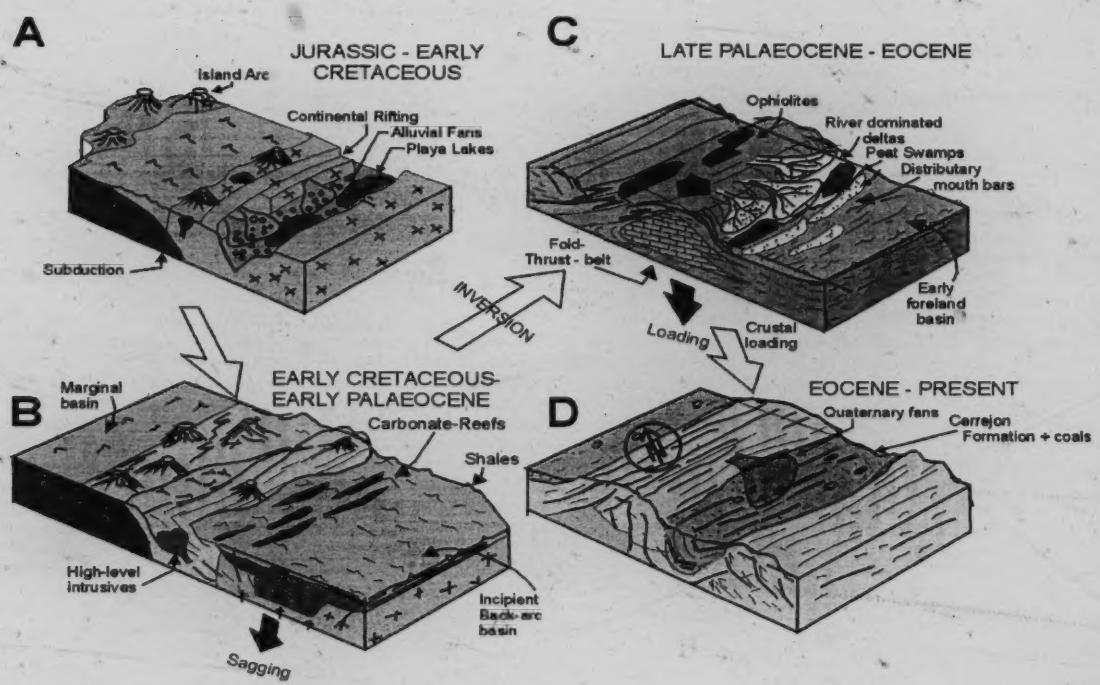

Figure 3.3 Sedimentary Environments

The depositional setting at the time when the Cerrejón Formation, including the coals, were deposited, is uncertain but certain key features suggest that a fluvio-deltaic setting prevailed for most of this period. The various subenvironments are depicted in Figure 3.3 where an interpretation of the depositional processes and setting is presented.

Regional studies indicate that the Cerrejón coal succession was formed in a shallow-water environment and in a slowly subsiding foredeep basin ahead of a foreland thrust belt. It is doubtful whether the basin was open or even connected to a proto-Caribbean sea. The coals were formed in those parts of the succession representing the upper delta plain deposits where extensive peat swamps existed uninterruptedly over exceptionally lengthy periods of time. A humid climate is assumed to have prevailed in this part of the basin throughout the mid- to late Paleocene.

CHAPTER 4 LA GUAJIRA FIELD HISTORY

4.1 INTRODUCTION

Since April 1994, Ecopetrol and a private investor group have conducted a coalbed methane exploration program in the Cesar-Rancheria Valley in Colombia. The project area is comprised of two noncontiguous areas, a northern area known as the Cerrejón region and a southern area known as the La Loma/La Jagua region. The Cerrejón region covers 79,000 acres while the La Loma/La Jagua region covers 168,000 acres. The exploration period was divided into two distinct phases. Phase I required the drilling and evaluation of three core holes in the project area and was finished in 1994. Phase II required the drilling and completion of 25 production wells, named Guajira No. 1 to 25. The drilling and completion was finished in November 1998.

Phase I of the exploration period can best be described as a preliminary assessment phase. Three core holes, the CH-1, 2, and 3 were drilled in this phase. Favorable rank and gas content data were derived from the CH-2 located centrally in the Cerrejón region.

Based on the favorable results obtained from the CH-2, a twenty-five well production test program in the Cerrejón region was proposed for Phase II.

The wells were located in the general area of the CH-2 and were drilled to evaluate the productivity of the area. All twenty five wells have been drilled, with 1 to 7 coal seam intervals completed in each one. With some exceptions, each well was drilled and completed with the same basic technique. They were drilled with a bentonite based mud system, cemented with a class A cement with gilsonite for lost circulation, perforated with 0.38-inch diameter shots delivered through a hollow steel carrier, and fractured with a 25-pound guar gum gel with a borate cross linker. The target sand amount was 5,000 pounds per net foot of coal and the target sand concentration was 5 pounds per gallon (PPG). The only exception to the above described fracture plan was an openhole completion attempted on well Guajira - 21. The interest of the present study is focused on five wells only, Guajira No. 21 to 25.

Geologically, the findings on these twenty five wells supported the predicted coal depths and confirmed the vast quantity of coal that is present in the central Cerrejón area. From an engineering standpoint, the coals have proved difficult to stimulate and produce. Screen out problems were encountered in many of the zones. The principal cause of these problems is thought to be the initiation of multi-fractures rather than one primary, predominant fracture. Other possible causes are tortuosity, coal spalling, and high lateral stresses. The completed zones exhibit low productivity, either occurring naturally due to low permeability or as a

result of formation damage caused during drilling, cementing, or stimulation. The Guajira - 25 well initially demonstrated favorable productivity both in water and gas volumes, however in mid-December 1998, a concurrent drop in the gas production rate, fluid level, and water production rate was observed. Previous production occurrences such as this was the result of sand and/or coal heaving into the wellbore and covering a completed interval. This was not the case in this instance. It is currently suspected that migration of coal fines in the reservoir is the cause.

Important information has been gained in Phase II of the exploration phase of the Guajira project, but much more information is yet needed to assess the coalbed methane potential in this area.

4.2 DRILLING WELL DESIGN

During well design, a strong effort was made to emulate programs that have proven effective for the commercial production of multiple seam coalbed methane wells, like those found in the Black Warrior Basin in Alabama. It was understood that, as experience was gained in the Guajira area, modifications would be implemented to reach the planned objectives. Tables 4.1, 4.2 and 4.3 present the general overview of each of the programs for drilling, casing and cementing, respectively.

Section	Depth – feet	Hole Size- Inches	Casing Size,Grade & Weight
Conductor	+/- 40	17 ½	13 3/8 inches, J55, 48 pound/foot
Surface	+/- 600	12 ¼	8 5/8 inches, J55, 24 pound/foot
Production	+/- 3000	7 7/8	5 ½ inches, J55, 15.5 pound/foot

Table 4.1 Hole and Casing Size

Section	Size & Type
Bit	7 7/8 inches Tricone, Reed HP 51X Type 2
Near Bit Stabilizer	7 13/16 inches
Drill Collar	6 inches
Integral Blade Stabilizer	7 13/16 inches
Drill Collars	6 inches
Drill Pipe	4 ½ inches, EX95, 20 pound/foot

Table 4.2 Drill String and Bottom-hole Assembly Sequence

The drilling fluid used was a bentonite based mud with caustic soda, Benex, and Polypac as additives. Mud weight varied from 8.6 to 9 PPG. Air drilling was attempted but abandoned after an unsuccessful try. A complete set of compensated density/gamma ray/caliper logs were ran in each well.

Additive	Characteristic
Cement	Class "A"
Yield	1,538 RPM
Water	6.04 gallon/sack
Slurry Weight	14.5 PPG
Excess	25 - 30%
Approximate Thickening Time	4 hours 15 minutes
Additive 1 – Gilsonite	18%

Table 4.3 Production Casing Cement Design

4.3 COMPLETION AND STIMULATION DESIGN

After the drilling operation of each individual well, a completion program was designed in order to set up the wells. Once the wells were perforated and cased, the remaining fluid, mud, was displaced and replaced with formation water gathered from previous wells. A set of cased hole logs, cement bond log/gamma ray/casing collar locator, were ran to check the integrity of the cement around the casing specially in the interval where the coal seams of interest were located. Perforation guns with a external diameter of 0.38 inch, a density of 4 shots per foot (SPF) and 90 degree phasing delivered through hollow steel carrier were deployed in sequential order while the fracturing jobs were carried out.

The fracturing jobs were carefully planned and designed jointly with specialized service companies in order to reach maximum effectiveness, and obtain the best results with the minimum damage to the formation. Table 4.4 summarizes the fracturing jobs.

Pad Size	30 %
Total Design Sand	5000 pounds/foot of coal seam interval
Max. Design Sand Concentration	5 pounds/gallon
Sand Size	12/20 Mesh
Gel Type	25-pound gum with borate crosslinker
Pump Rate	25 BPM

Table 4.4 Fracture Job Design

Five and one half inch fracture plugs were set between each coal seam interval. The perforations were broken down with a two-stage, 5 barrel per stage, acid treatment (28% HCl). Tables 4.5 and 4.6 show the pre-acid breakdown solution and the fracture job carried out in each of the coal seams stimulated in the Guajira project.

Stage	Volume – gallon	Rate - gallon/minute
Pre – Acid	420	10
Acid	210	5
Flush	2,386	56.8
Flush	210	5
Acid	210	5
Flush	0	0

Table 4.5 Breakdown design

Stage	Sand Con.		Stage Vol.		Gel Vol.	Sand Wt.	Cum. Sand	Water Vol.	Water Vol
	Start	End	bbl	gal	bbl	lb	lb	gal	Bbl
Prepad	0	0	10.0	420			0	420	10.0
Pad	0	0	200.0	8,400	200.0		0	8,400	200.0
1	0	1	50.0	2,100	50.0	1,050	1,050	2,100	50.0
2	1	2	50.0	2,100	50.0	3,150	4,200	2,100	50.0
3	2	3	100.0	4,200	100.0	10,500	14,700	4,200	100.0
4	3	4	100.0	4,200	100.0	14,700	29,400	4,200	100.0
5	4	5	100.0	4,200	100.0	18,900	48,300	4,200	100.0
6	5	5	55.7	2,340	55.7	11,700	60,000	2,340	55.7
Flush			60.9	2,556	0.0	0	60,000	2,556	60.9

Table 4.6 Fracture Schedule Design

4.4 PRODUCTION EQUIPMENT

Once each well had been stimulated through the selected coal seams, the hole was cleaned out with formation water. Then, the production string was run into the hole and lined up on surface with the production equipment. Table 4.7 describes the production equipment installed in each well of the Guajira project.

Equipment	Description
Tubing	2 7/8 inches, 6.5 pound/foot, grade J55
Rods	7/8 inches, Class D
Down hole Pump	2 inches OD x 12 feet long pump
Pumping Unit	Model C160D-200-74
Prime Mover	25HP, 460V, 1125 RPM Electric Motor

Table 4.7 Production Equipment

All equipment was tested and hooked up to the measurement and control tools required for the appropriate mechanical work. They were made ready to begin the production phase.

4.5 PRODUCTION DATA

The wells have been evaluated from two different points of view, either counting the performance of each one individually, or together as a field case. Four of the wells were completed and cased to total depth and stimulated with hydraulic fracturing. Only well Guajira - 21 was completed leaving an interval in open hole.

4.5.1 Well Guajira - 21

Well Guajira - 21 was placed on production in December 1996 with a 1.5-inch external diameter down hole pump set at 662 m running at 9 strokes per minute (SPM). Initial water production was 80 to 90 BPD while gas production was 6 to 8 MCFD. The water production declined to 60 BPD and the gas production remained constant at 6 to 8 MCFD. Attempts were made to lower the pump below the lowest completion, but coal heaving into the wellbore prevented this from being workable. The wellbore was cleaned out several times but the problem persisted.

The water and gas production from this well were low in light of the net feet of coal that were successfully stimulated. The low flow rates are indicative of low permeability or formation damage. Production history of

this well is depicted in Figure 4.1. Appendix B.1 provides the history and configuration of this well leading to production.

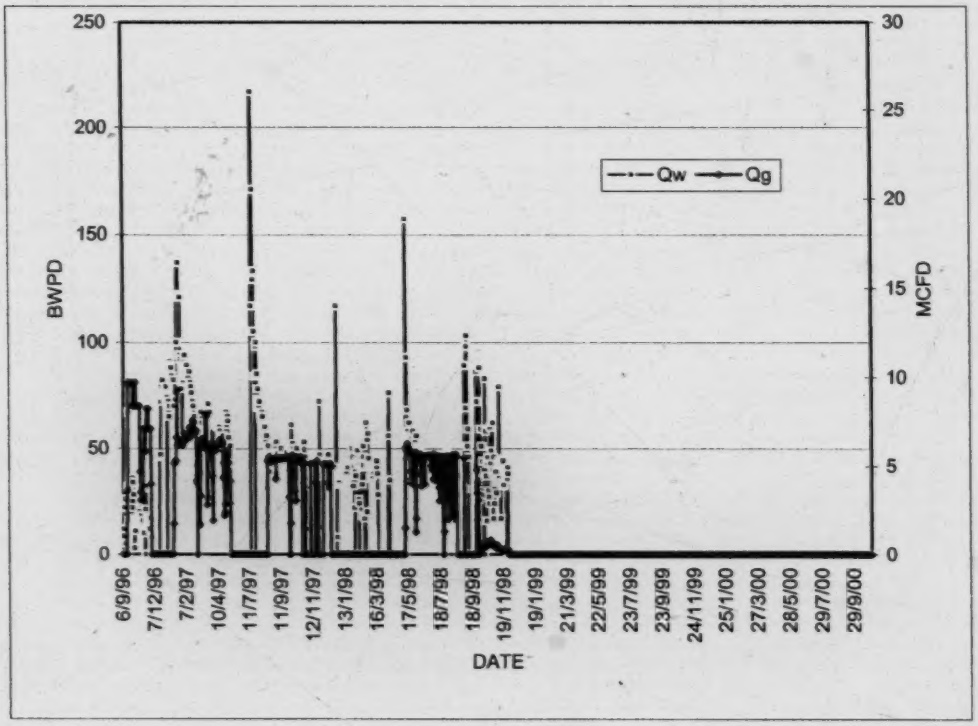

Figure 4.1 Well "Guajira - 21" Production History

4.5.2 Well Guajira - 22

Well Guajira - 22 began pumping in late July 1998. The pumping system was configured to produce 150 BPD. The well was initially pumped with the casing closed, and the surface pressure built to 600 psi over a period of three days. The gas pressure was lowered to and held at 150 psi using a backpressure regulator. The water production rate was reported at 50 to 60 BPD during this time. The backpressure held on the well was gradually reduced to zero, but the reduction seemed to have little effect on the water production rate. This was contrary to expected results.

In this well, an eight-foot coal seam at a depth where gas contents should be at or near their maximum volumes was stimulated according to the fracture design. Even though the other zones could not be successfully stimulated, the combined fluid production for the eight-foot seam is less than desirable. Low permeability and/or formation damage are suspected. The production histories of gas and water are presented in Figure 4.2. Appendix B.2 provides the history and configuration of this well leading to production.

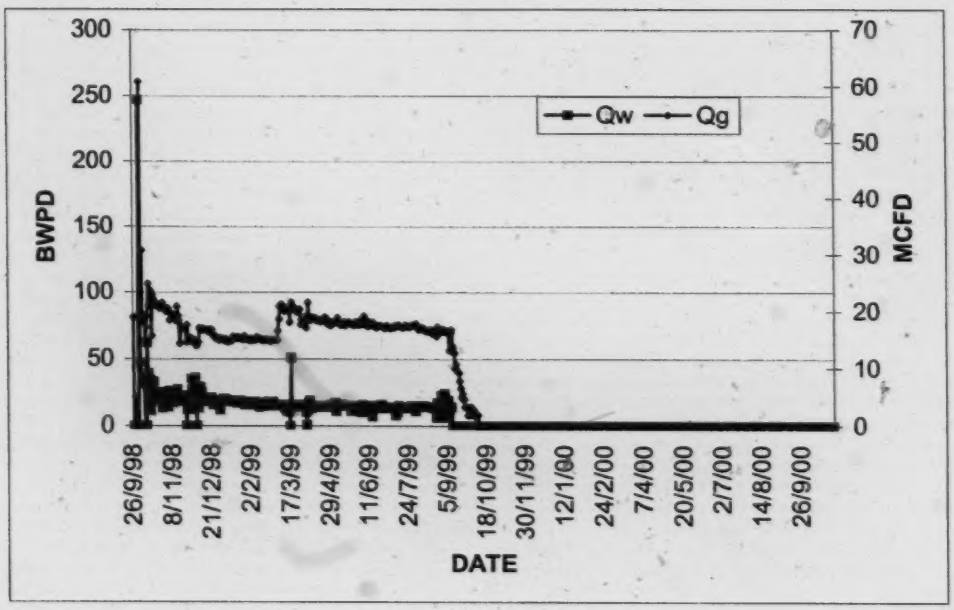

Figure 4.2 Well "Guajira - 22" Production History

4.5.3 Well Guajira – 23

The beam pump system on well Guajira - 23 was set up to produce about 250 BPD. The pump was started in early December 1998. The water production rate was measured at 176 barrels of water per day (BWPD). Soon, the instantaneous water production rate decreased to 65 BWPD. The pump was pulled to check for mechanical problems. Coal particles had caused the plunger to become stuck in the pump barrel. After finding this problem, the bottom of the hole was checked to see if any fill had occurred. The bottom was found at 793 meters indicating that 7.7 meters of fill was in the well. While cleaning out the wellbore, samples of the circulated material were taken. Sand, fairly large pieces of coal, and a few small pieces of cement were all present in the fluid. The tubing, rods, and pump were run back into the hole and production was again commenced.

The production profile of this well resembled that of well Guajira - 22. Water production was initially between 60 and 70 BPD, but within one week, had dropped to 30 BPD. Gas production increased from 3 MCFD to up to 9 MCFD during this one-week period. Since then, gas and water production have been on a slow and steady decline, Figure 4.3 shows the production history of this well. Appendix B.3 provides the history and configuration of this well leading to production.

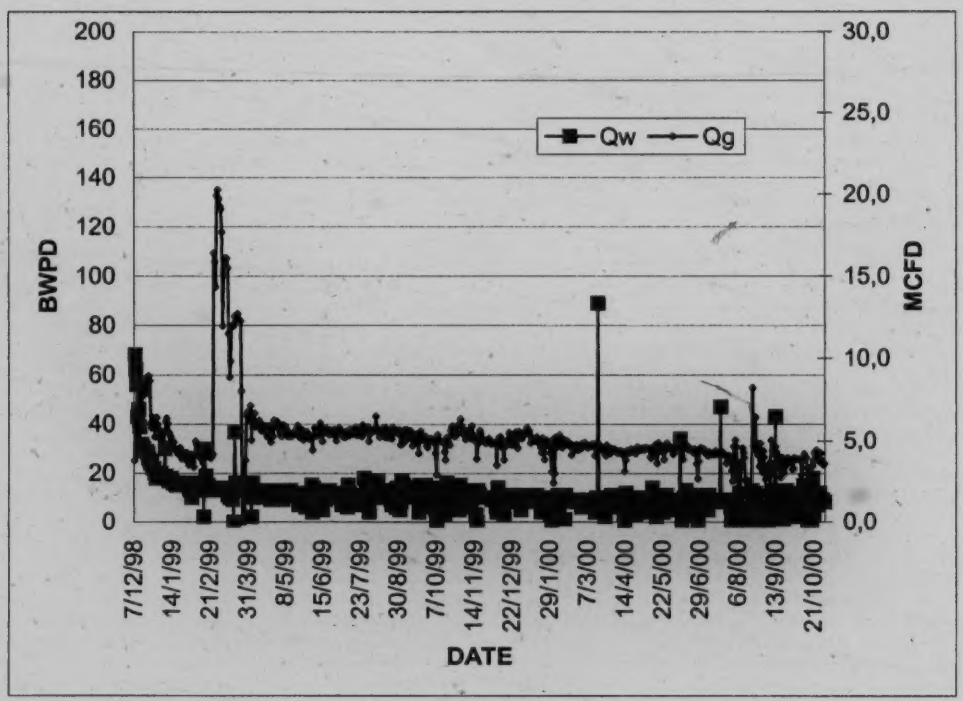

Figure 4.3 Well "Guajira - 23" Production History

4.5.4 Well Guajira - 24

The production history of well Guajira - 24 is shown in Figure 4.4. Early in the production phase, this well produced for a very short time the equivalent to 200 MCFD of methane gas, but declined sharply. The water production instead, has kept a constant behave. The peak of gas production and the constant shape of the water curve, always above of the gas one, is a typical indication of liberation of free gas from the coal seam, and not gas disorbing process from the coal surface.

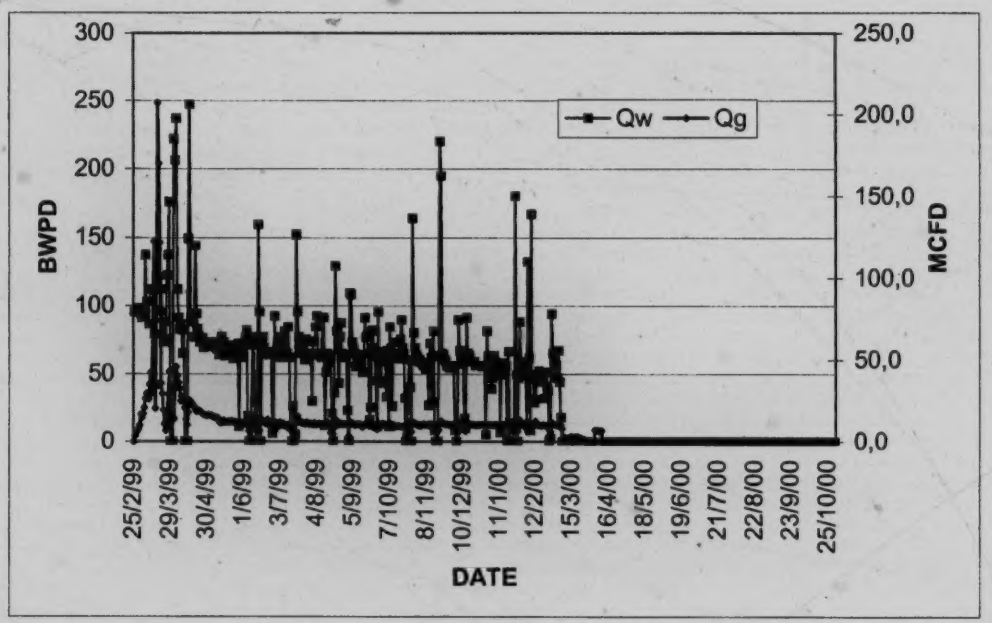

Figure 4.4 Well "Guajira - 24" Production History

Appendix B.4 provides the history and configuration of this well leading to production.

4.5.5 Well Guajira – 25

In mid-August 1998 well Guajira - 25 began pumping at a rate of 130 BWPD. This rate reflected the mechanical configuration of the pumping equipment, not the productivity of the well. The fluid level remained within 92 meters of the surface while pumping. After two weeks of production at this rate, the pumping unit speed was increased to bring about an increase in water production. Spurious water rate and gas pressure readings were recorded for the next month. Causes of the variations can be attributed to power outages. The data collected until late September are quite suspect and are not included in the production history.

An orifice meter was installed, calibrated, and put into service in September 1998. The gas production was measured at 10 MCFD. This early onset of gas production, which accompanied only a modest drawdown in pressure, indicates that the coal seams are near their gas saturation point. Water production rates still varied in a manner that was inconsistent with the fluid level. In October 1998, a mechanical problem was discovered with the seating nipple and corrected. The well was put back on production. Water production rates as high as 400 BWPD were

calculated from bucket tests. Errors in the testing are likely, as this would yield pump efficiencies of over 100%. The target production rate was 300 BWPD, and this rate was achieved.

From this point on, this well began to exhibit classic coalbed methane well performance. The fluid level slowly declined as the gas rate increased. By early December, the gas production rate had climbed to over 50 MCFD, the water production rate was roughly 300 BWPD, and the fluid level had dropped to about 369 meters. A power loss occurred on December 4, and was not restored until December 7. The fluid level rose and the gas production declined as expected during this period. When the power was restored and the beam pump began operating again, water production was over 300 BWPD and gas production slowly rose to its pre-outage level. On December 17, the gas production peaked and then began a downward trend, as did the water production and fluid level. A drop in water production combined with a drop in fluid level is usually indicative of sand/coal in the wellbore covering a set of perforations. On December 28, the well was cleaned out. Only 9 meters of fill were found in the wellbore, placing it about 22 meters below the lowest set of perforations. The tubing, rods, and pump were run back into the hole, seating the pump at 830 meters.

The well has not sustained production over 50 MCFD since it has been cleaned out. It is currently producing about 35 MCFD and 220 BWPD. At this time, fines migration into the fracture, aggravated by the cyclic nature of production, is suspected. Figure 4.5 gives the production history of the well. Further study will be necessary to verify if the location of this well is the best for performing as a CBM reservoir.

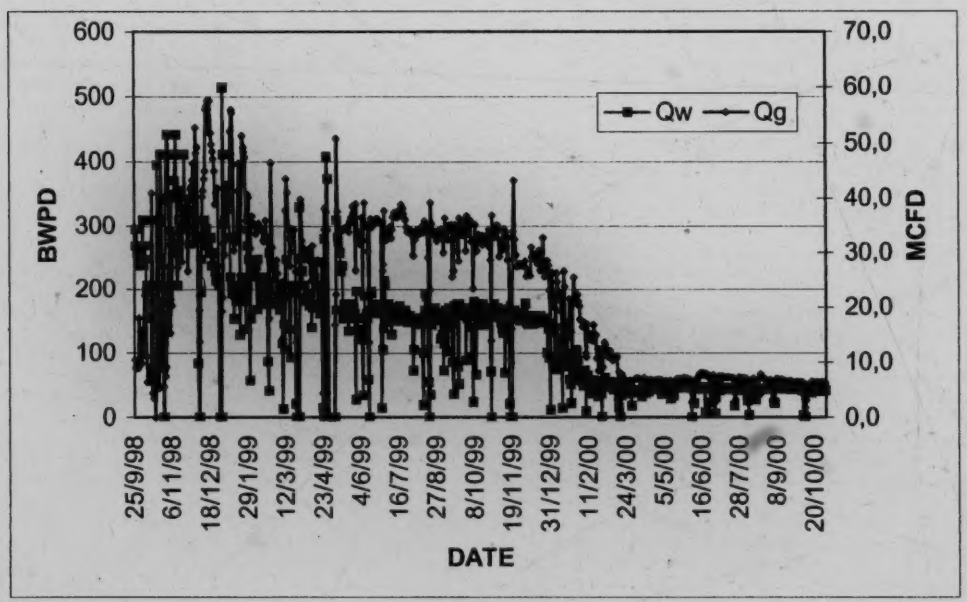

Figure 4.5 Well "Guajira - 25" Production History

Appendix B.5 provides the history and the configuration of this well leading to production.

4.6 COMPOSITIONAL GAS ANALYSIS OF LA GUAJIRA FIELD

Produced samples taken from La Guajira field were analyzed to determine gas composition. The analyses were carried out on three samples of gas taken at each well head, according to the standard method of the service company contracted. Table 4.8 gives the results of these analyses.

The samples were taken at 100 psi and 80 ^{0}F. Their characteristics are:

- Average molecular weight = 16.44
- Calculated gas gravity = 0.568 (air = 1.00)

Power parameters at 14.65 psia and 60 ^{0}F (standard conditions) are:

- Gross heating value = 996.47 Btu/scf
- Net heating value = 897.31 Btu/scf
- GPM (C_3^+) (Gallons of condensate per thousand cubic feet of gas)= 0.015

Component	Mol (%)	GPM	Weight (g)	Heating Value (Btu /scf)
Methane	98.40	0	15.79	993.81
Ethane	0.06	0	0.02	1.12
Propane	0.01	0.002	0.00	0.18
Iso – Butane	0.02	0.007	0.01	0.71
n – Butane	0.00	0.000	0.00	0.00
Iso – Pentane	0.00	0.000	0.00	0.00
n - Pentane	0.00	0.000	0.00	0.00
Hexanes Plus	0.01	0.006	0.01	0.66
Carbon Dioxide	1.19	0	0.52	0
Nitrogen	0.31	0	0.09	0
*Hydrogen Sulfide	-	-	-	-
Total	**100.00**	**0.015**	**16.44**	**996.47**

Table 4.8 Gas Composition Results from La Guajira Field.

* Hydrogen sulfide was negligible

CHAPTER 5 TRIAXIAL TEST RESULTS

5.1 INTRODUCTION

Coalbed methane wells usually require stimulation techniques because their initial flow rates are quite low in the early stages of production. Open hole cavity completions are an alternative stimulation technique for this type of reservoir.

A select group of core samples from La Guajira field were tested in the laboratory with the objective to determine strain stress properties of the coal seams. These properties are then used to help assess the potential for openhole cavity completions in coalbed methane wells in a reservoir in the northern part of Colombia.

Core samples obtained from a local coal mine were obtained from a depth interval that did not closely correlate with coal seams present in the coalbed methane wells. Unfortunately, samples obtained from coalbed methane wells were cored many years ago and due to improper storage, were badly damaged and very oxidized. Therefore, it was decided not to use these "old" samples in our tests, even though they were actual reservoir core specimens.

5.2 TEST OBJECTIVE

The objective of the triaxial tests were to determine the mechanical rock properties of La Guajira field cores in order to evaluate the possibility of applying an openhole cavity completion technique to a coalbed methane reservoir.

5.3 SPECIMEN DESCRIPTION

The general properties of the coal seams were estimated from routine proximate tests in the local coal mine. They were then generalized for the amount of coal seams of the coalbed methane wells in order to give a broad idea of their components as part of this work. Proximate test results are presented in Table 5.1

Component	Content - %
Water Content (= V_W/V_T)	1.3 - 1.7
Volatiles	32 - 37
Fixed Coal	45 - 48
Ash	11 - 14
Others	10.7 – 0.3
Gas Content	320 – 480 cf/ton
Heating Value	10,200 - 11,000 BTU/lb

Table 5.1 Proximate test results from La Guajira Coal Seams.

Core samples taken from the local coal mine were coated with a non-reactive wax and wrapped with aluminum foil paper. Then they were placed in a PVC pipe, labelled and stored at –10 °C temperature to avoid oxidization. The frozen core specimens are illustrated in Figure 5.1.

Prior to beginning the testing program, the samples were trimmed to the appropriate length and the ends were polished flat, as shown in Figures 5.2 and 5.3. Each sample was measured and weighed prior to testing and the results are provided in Table 5.2.

Sample No.	Depth of Burial (m)	Length (mm)	OD (mm)	Bulk Density (g/cc)	Mass (g)
Core – 0	145.00	134.31	63.24	1.23	520.00
Core - 1	141.00	120.83	63.34	1.22	466.32
Core – 2	174.80	113.04	60.71	1.16	382.44
Core – 3	172.30	133.26	63.10	1.21	504.20

Table 5.2 Core Specification from La Guajira Field.

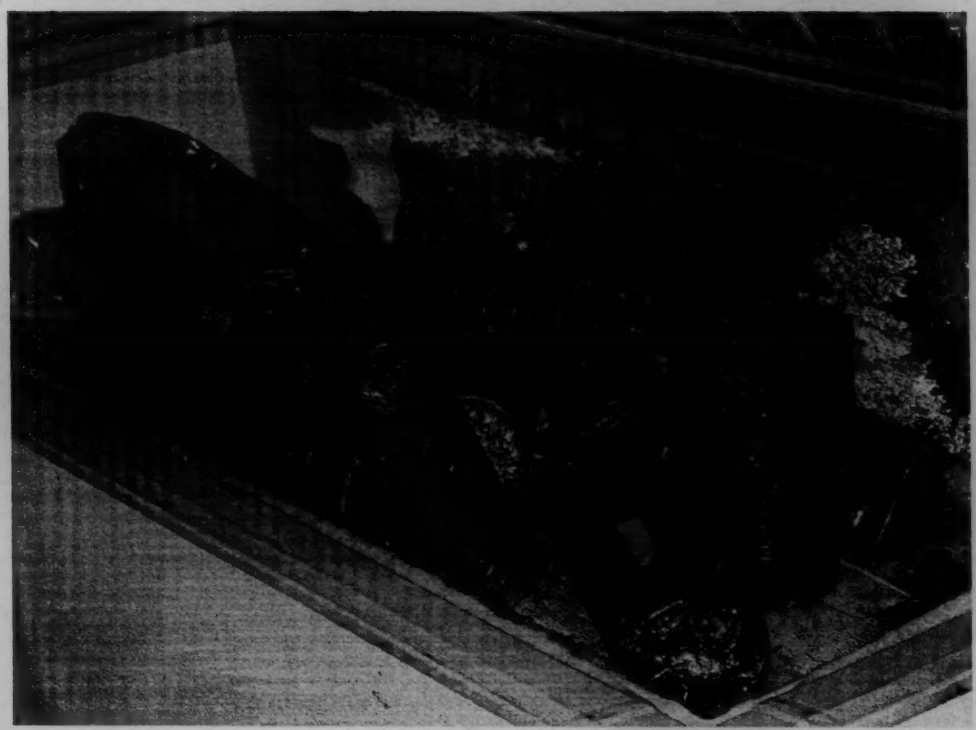

Figure 5.1 Core Conserved at Low Temperature

5.4 TEST PROCEDURE

A consolidated drained triaxial test is performed by placing a specimen in the cell chamber, introducing lateral pressure, then allowing the specimen to consolidate (allowing drainage) under the all-around confining pressure. The sample is then allowed to drain as axial load is applied, so that excess pore pressures do not develop. Consolidated drained tests may take considerable time to complete because of the time required for both consolidation under the confining pressure and drainage during application of axial load (Bowles, 1992).

In combination with a series of photographs, the following describes the procedures used to test the specimens from La Guajira field in the triaxial cell:

- Calibrate all the required sensors, appendix A contains the calibration data.
- Trim core to a required external size and length (Figures 5.2 and 5.3).
- Carefully place the specimen inside a stretched membrane (Figure 5.4).
- Secure the sample inside the membrane using rubber strips or bands, and position it to the top plate of the cell base.

- Carefully install the necessary electric lines of the data acquisition and take the initial readings (Figure 5.5).
- Assemble the cell with the cell cap and tighten each bolt (Figures 5.6 and 5.7).
- Place the cell in the compression machine (Figure 5.8).
- Attach deformation dials both internally and externally, to measure the sample deformation (Figure 5.8).
- Fill the cell with silicon oil.

Figure 5.2 Rough core from La Guajira Field.

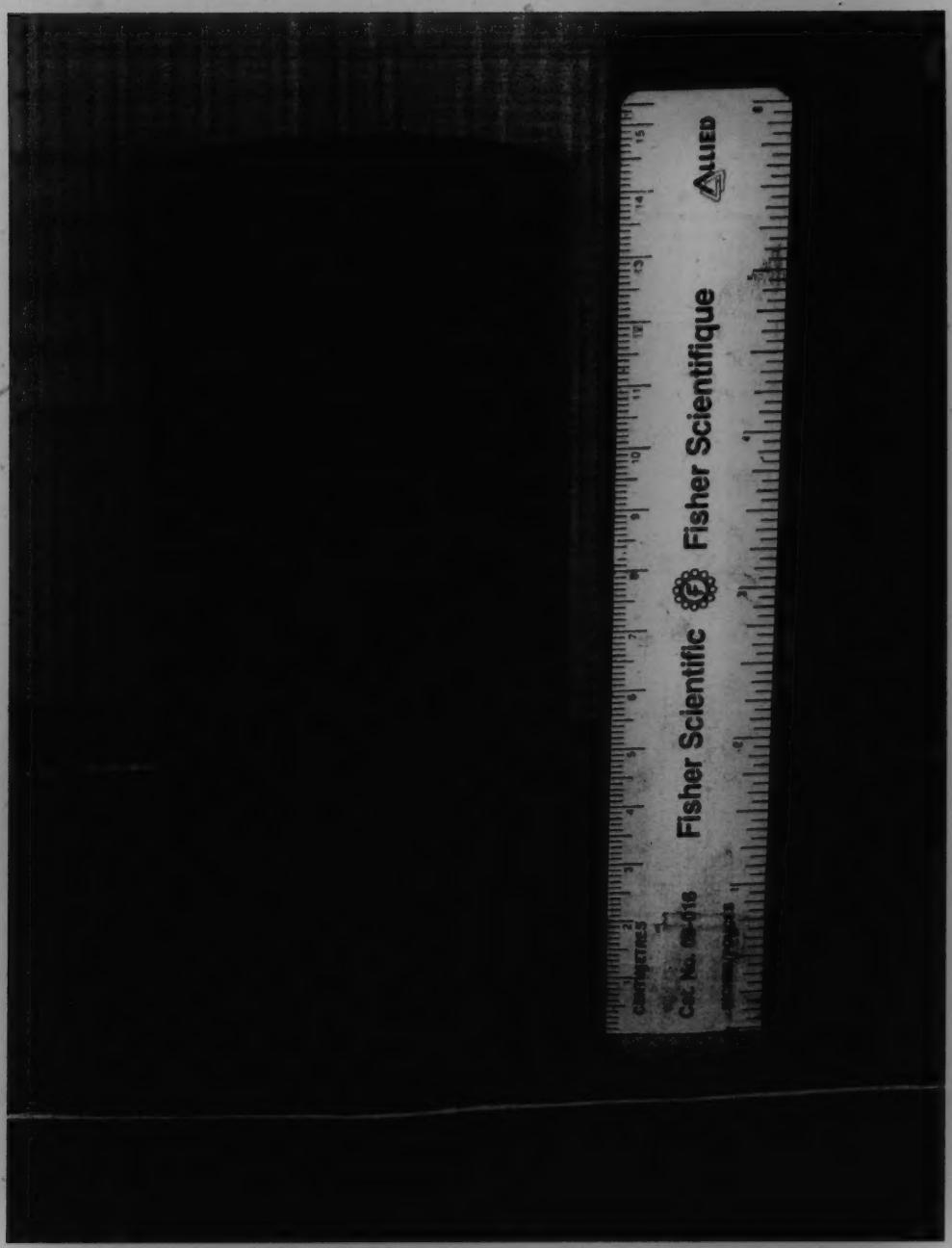

Figure 5.3 Core Finished and ready to test

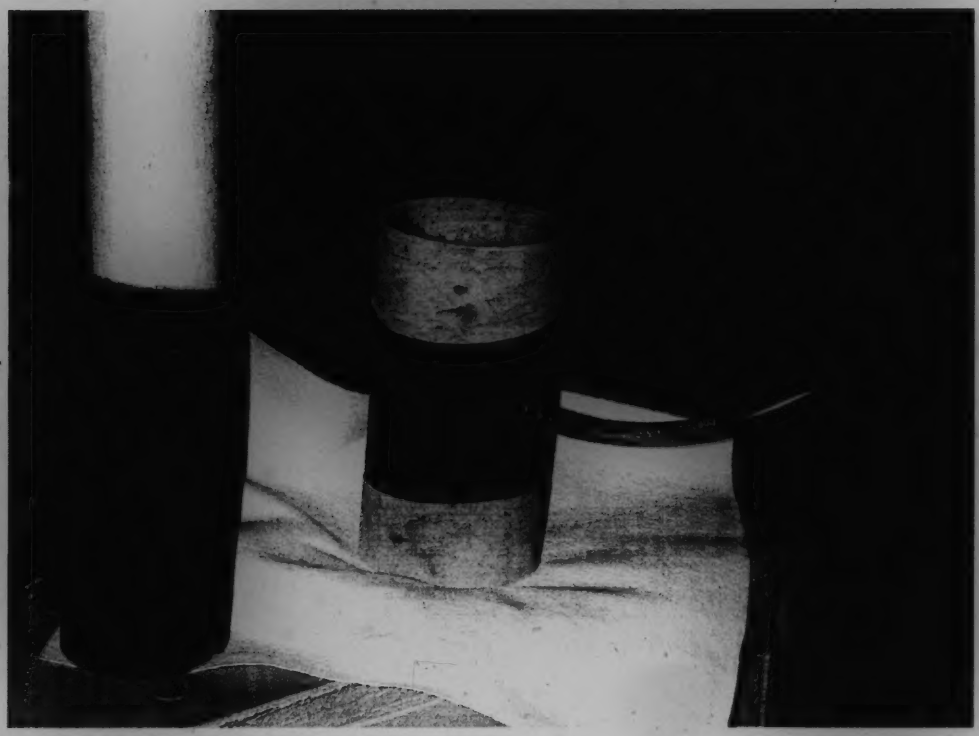

Figure 5.4 Membrane to cover the Core

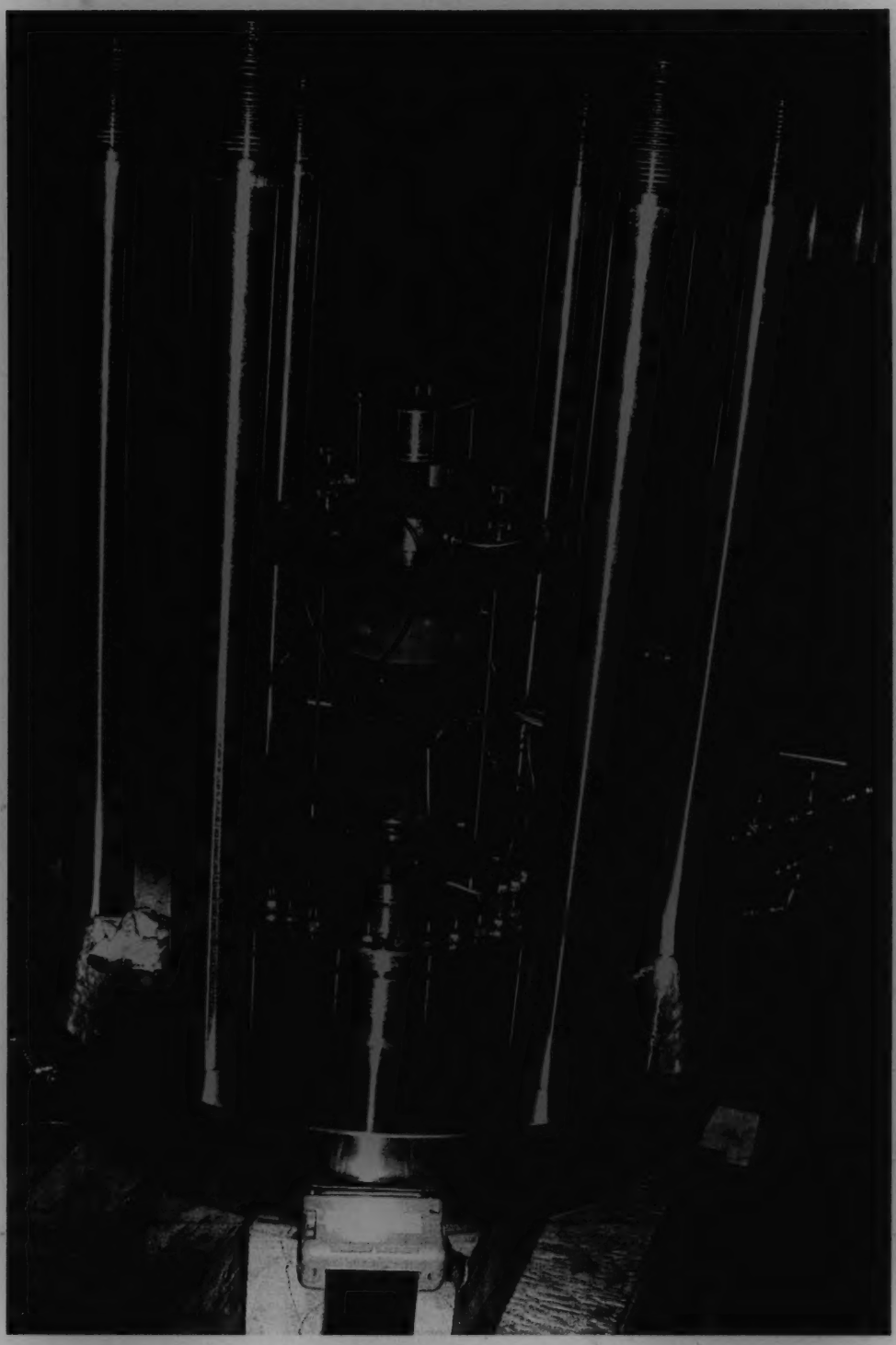

Figure 5.5 Core installed in Triaxial Test Base

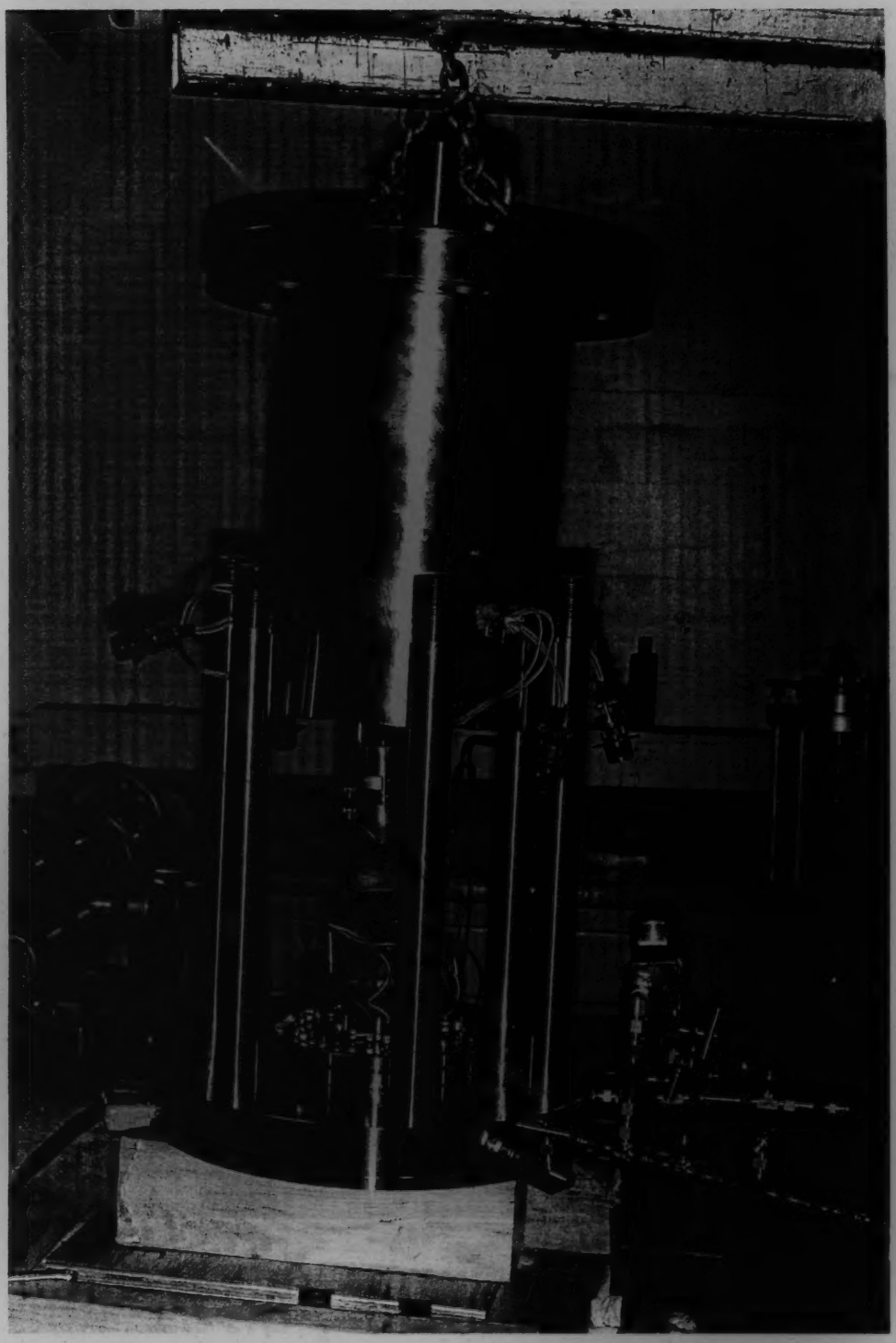

Figure 5.6 Cell Assembling Top Cap

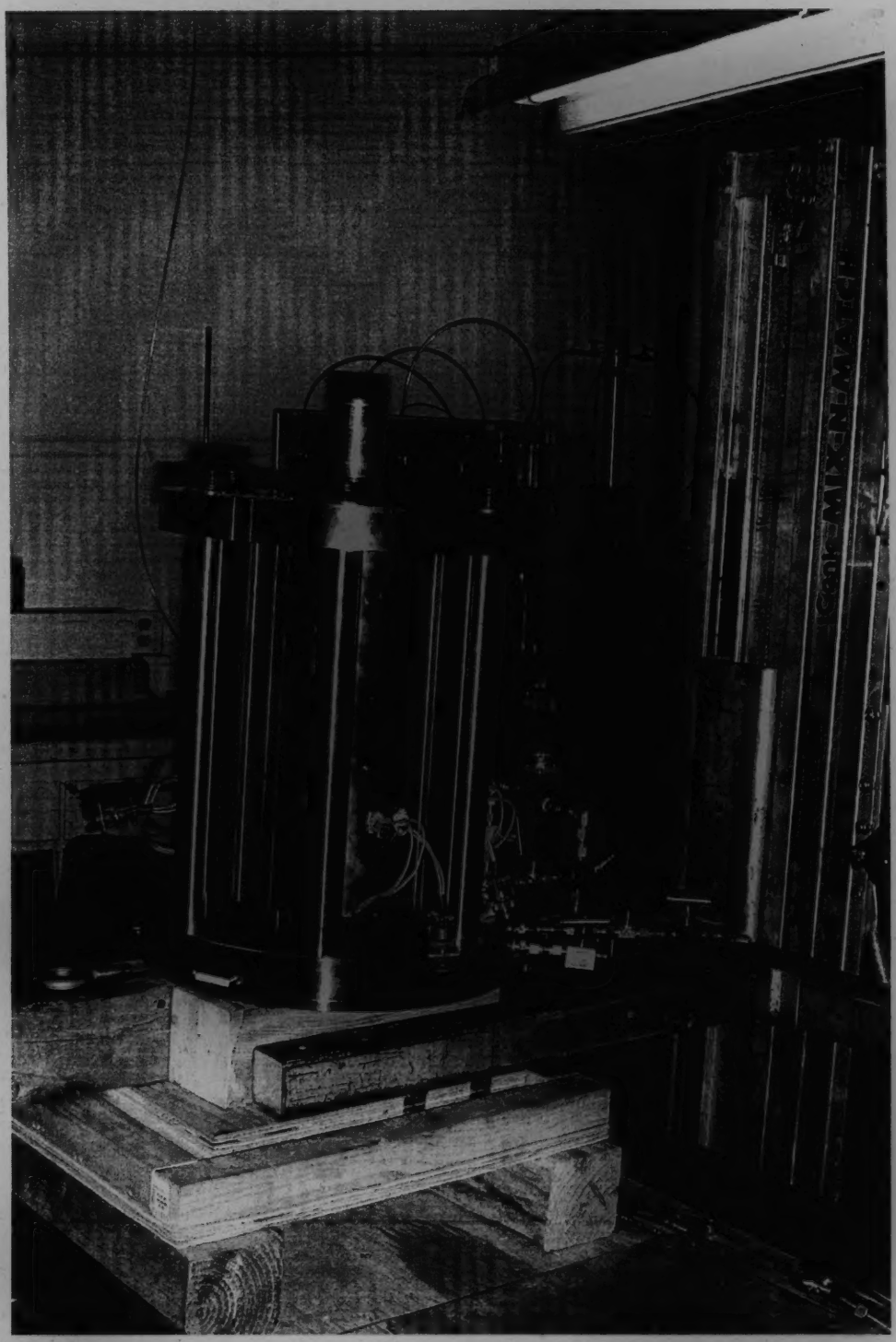

Figure 5.7 Triaxial Cell With Top Cap

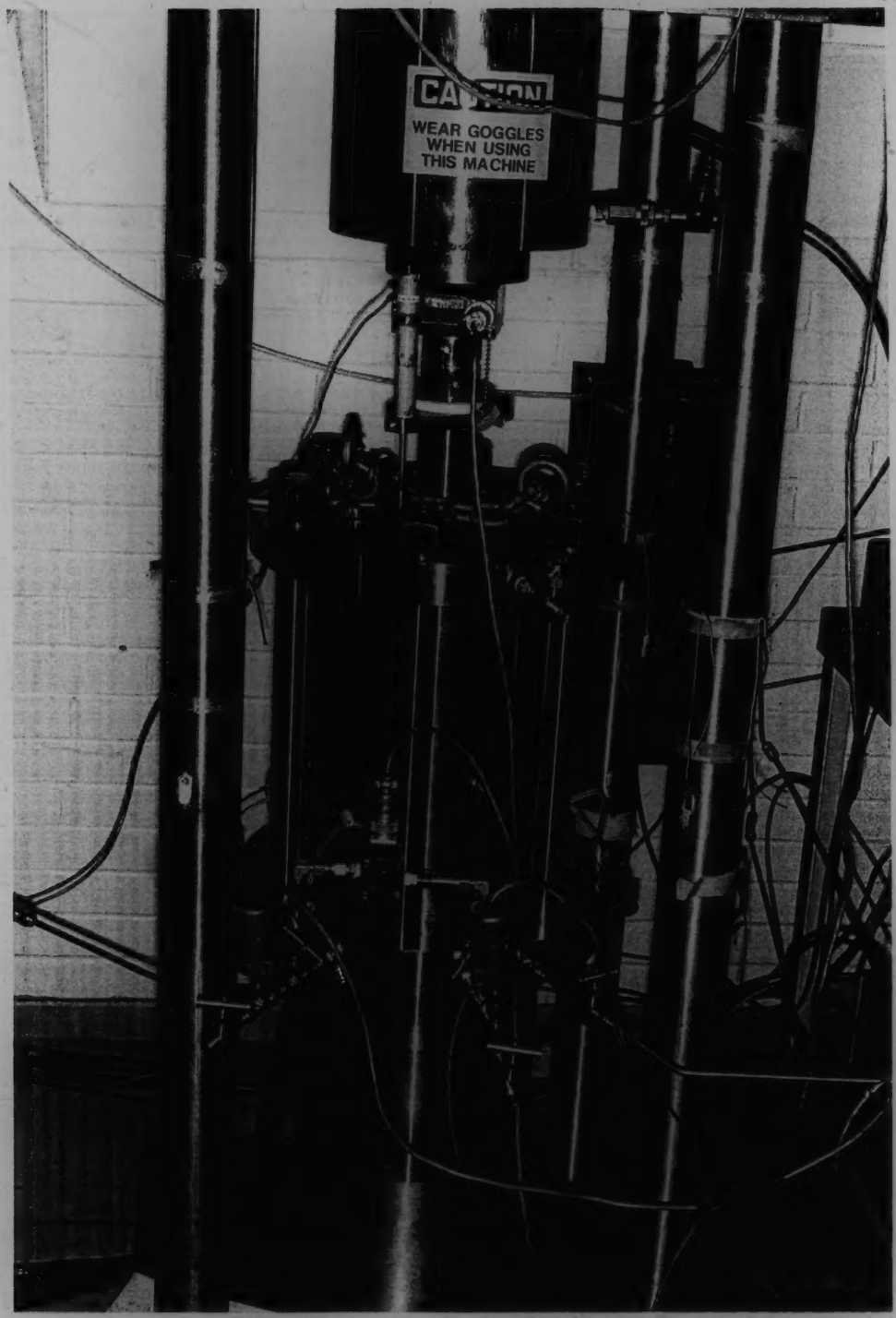

Figure 5.8 Cell Installed in its base and lined up with accessories

- Using the cell pressure pump, apply a predetermined lateral pressure (σ_3) to the cell and simultaneously reduce the vacuum on the interior of the sample to zero.
- Saturate the sample with water and use the B test to verify the level of saturation of the sample.
- Once the sample is saturated, shear the sample and measure the process until the sample fails.
- After the sample has failed, shut off and reverse the compression machine.
- Release the chamber pressure, and remove the sample load.
- Remove the deformation equipment and remove the triaxial cell from the compression machine. Figures 5.9 and 5.10 illustrate a failed core.
- Disassemble and clean as necessary, prepare a new specimen to the same approximate density and repeat the same steps for the required number of tests.

Figure 5.9 Core Sheared Still Inside the Membrane

Figure 5.10 Core Sheared

5.5 TEST RESULTS

The specimens from La Guajira Field were tested to determine the stress strain properties. The following sections describe the observations of the coal behavior from each test. Figures 5.11, 5.13, 5.15 and 5.17 show the final state of the specimens after the shear test.

5.5.1 Specimen Core – 0 (σ_3 = 0 kPa)

Specimen Core-0 failed through one of the planes that seem to be an interconnected natural cleat system with a weak point. The test had to be stopped once the failure was reached in order to evaluate, the primary failure plane of the sample. Figure 5.11 shows the post test state of Core-0. Figure 5.12 illustrates the stress strain response for Core-0.

Over the range of 0 to 0.5% axial strain, the coal response is nonlinear as fissures and cleats present in the core are closing. Beyond 0.5 % strain the coal exhibits linear elastic behavior up to the failure point. Once the peak load of 9500 kPa is reached at approximately 1.7 % axial strain, loss of strength occurs rapidly in a typical brittle material failure.

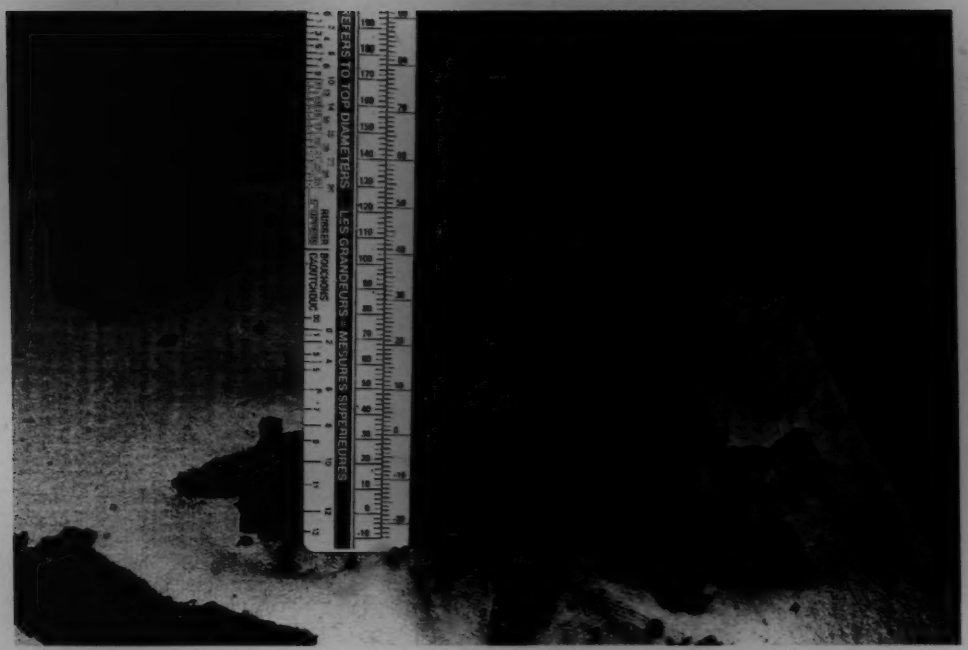

Figure 5.11 Core – 0 Sheared

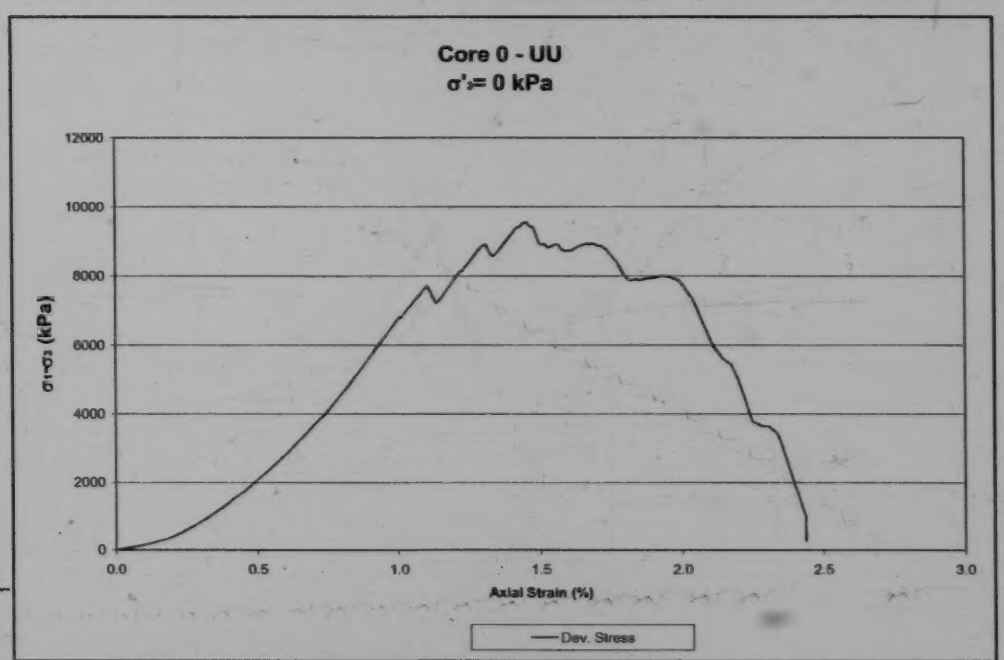

Figure 5.12 Core – 0 Strain Vs. Deviatoric Stress

5.5.2 Specimen Core – 1 (σ_3 = 200 kPa)

In a similar fashion to Core-0, Core-1 displays nonlinear behavior in the initial stage of the test when the fissures and cleats are closing. Figure 5.13 illustrates the post-test state of the core. However, as can be seen in Figure 5.14 this non-linear part of the curve is small due to the application of a confining stress of 200 kPa. Once the cleats and fissures are closed, the sample behaves linearly until the failure point is reached where a rapid loss of strength is representative of brittle material failure. As shown in Figure 5.14, the specimen initially contracts and then follows a constant period of zero volumetric strain. It is unclear whether this truly represents the specimen behavior or was an artifact of the strain measurement devices. Once the sample reached failure, clearly the volumetric strain of the Core-1 was dominated by a dilation process.

Figure 5.13 Core-1 Sheared

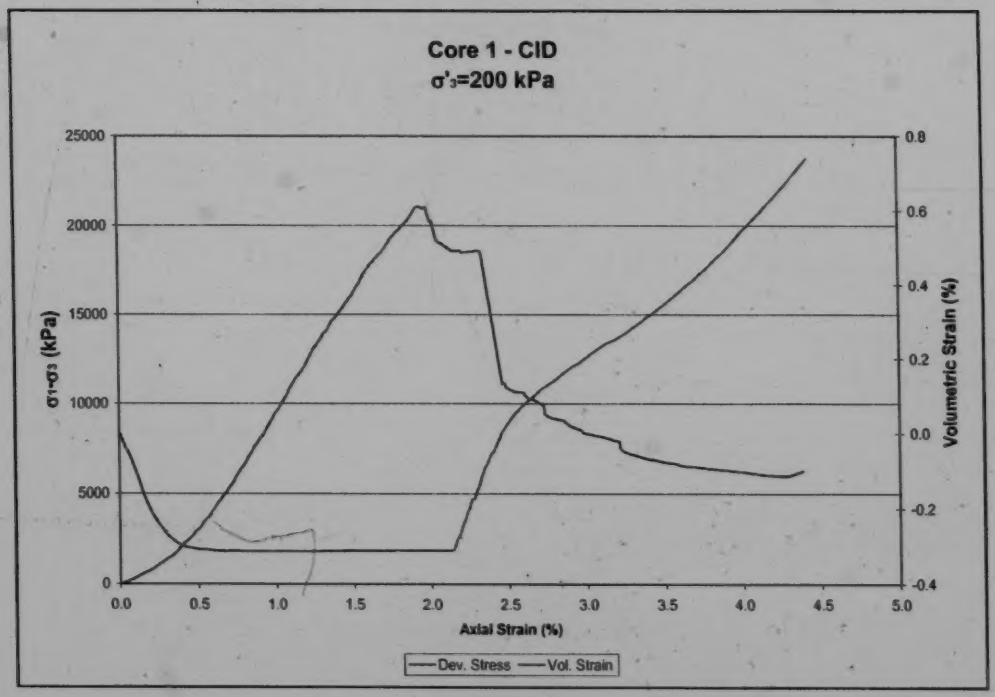

Figure 5.14 Core-1 at 200 kPa Confining Pressure.

5.5.3 Specimen Core –2 (σ_3 = 400 kPa)

Figure 5.15 shows the post-test condition of the Core-2. As illustrated in Figure 5.16, Core-2 also follows a behavior fairly similar to the previous cores; a small non-linear behaviour at the initial part of the test, followed by a linear elastic region and a sharp decline at the failure point, again characteristic of a brittle material. It's important to highlight that the strength of this sample was lower than the others because of the presence of a weak plane. As evidenced by the volumetric strain behavior, the

sample begins to dilate very early in the test, likely due to the presence of a rough but weak plane that induces early dilation, as illustrated in the post-test condition shown in Figure 5.15. The presence of the weak plane also helps explain the uncharacteristically low failure stress. The results of this specimen were considered unsuitable for defining the failure criteria of the coal and were not utilized during the analysis.

Figure 5.15 Core-2 Sheared

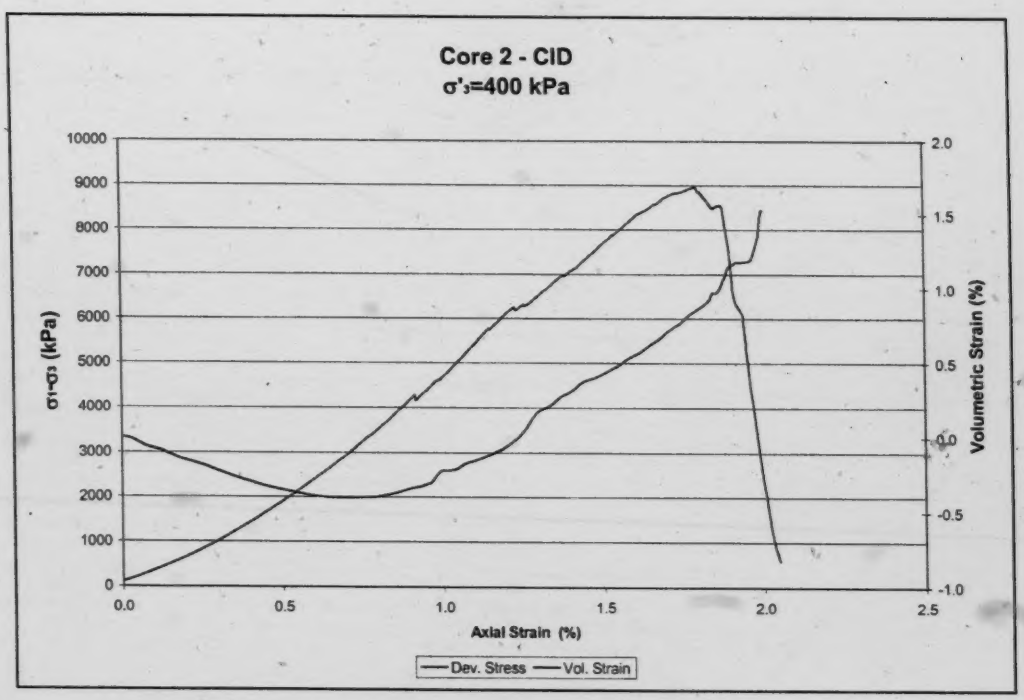

Figure 5.16 Core-2 at 400 kPa Confining Pressure.

5.5.4 Specimen Core – 3 (σ_3 = 1,000 kPa)

Figure 5.17 shows the post-test state of Core-3. As shown in Figure 5.18, Core-3 shows similar behavior as the other cores, especially, exhibiting linear elastic behavior right up to the failure point. Core-3's volumetric behavior shows a more typical homogeneous response with contraction occurring up to the peak strength and the rapid onset of dilation following failure. The rapid dilation is likely caused by shear displacement along the rough faces of shear planes developed during shear. The surface of a shear plane in Core-3 is shown in Figure 5.17.

Figure 5.17 Core-3 Sheared

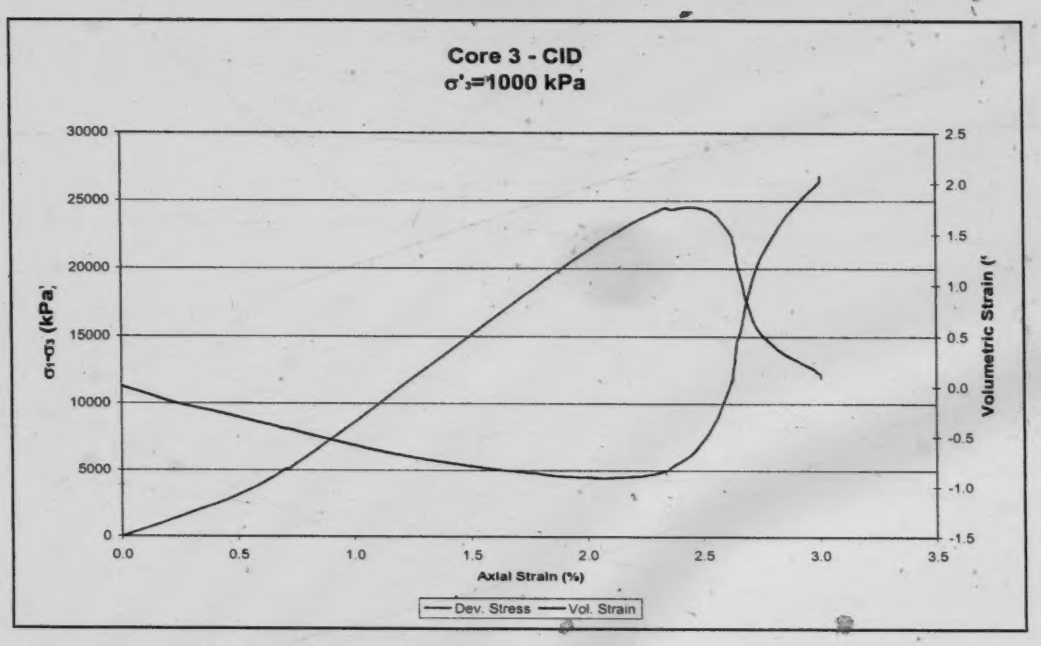

Figure 5.18 Core –3 at 1,000 kPa Confining Pressure

5.5.5 Shear Failure Criterion

The failure criterion concept that was applied to evaluate the coal seams from La Guajira is the Hoek and Brown failure criterion, which was developed for massive rocks and empirically modified to handle the deterioration in the properties of these rocks with decreasing rock quality (i.e. increasing fracture density). The Hoek and Brown criterion was originally developed in 1980 for estimating the strengths of hard rock masses. It is purely empirical and hence there are no "theoretical" ways to interpret the various relations derived from the criterion. The generalized form of the criterion is defined by:

$$\sigma'_1 = \sigma'_3 + \sigma_{ci} \left(m_b \cdot \sigma'_3/\sigma'_{ci} + s \right)^a \qquad [5.1]$$

where σ'_1 and σ'_3 are the major and minor principal effective stresses at the failure, respectively;

m_b is the value of the Hoek and Brown constant;

s and a are constants which depend upon the characteristics of the rock mass; and

σ_{ci} is the uniaxial compressive strength of the intact rock pieces.

In order to use the Hoek and Brown criterion for estimating the strength and deformability of jointed rock masses, three properties of the rock mass have to be estimated. These are:

- The uniaxial compressive strength σ_{ci} of the intact rock pieces in the rock mass,
- The value of the Hoek and Brown constant m_i for these intact rock pieces, and
- The value of the geological strength Index (GSI) for the rock mass.

For the intact rock pieces that make up the rock mass, the original equation simplifies to:

$$\sigma'_1 = \sigma'_3 + \sigma_{ci} \ (m_i \cdot \sigma'_3/\sigma'_{ci} + 1)^{0.5} \qquad [5.2]$$

The relationship between the effective principal stresses at failure for a given rock is defined by two constants, the uniaxial compressive strength σ_{ci} and the constant m_i. Wherever possible, the values of these constants should be determined by statistical analysis of the results of a set of triaxial tests on carefully prepared core samples (Hoek and Brown, 1997).

Unlike other rocks, coal is organic in origin and therefore has unique constituents and properties. Unless these properties are recognized in characterizing coal, the results of any test will exhibit a large amount of scatter (Hoek and Brown, 1997).

Most geotechnical software is written in terms of the Mohr and Coulomb failure criterion in which the rock mass strength is defined by the cohesive strength c' and the angle of friction. The linear relationship between the major and the minor principal stresses, σ'_1 and σ'_3, for the Mohr and Coulomb criterion is:

$$\sigma'_1 = \sigma'_{cm} + k\,\sigma'_3 \qquad [5.3]$$

Where σ'_{cm} is the uniaxial compressive strength of the rock mass and k is the slope of the line relating σ'_1 and σ'_3 and the values of ϕ' and c' can be calculated from:

$$\sin\phi' = (k-1)/(k+1) \qquad [5.4]$$

$$c' = \sigma'_{cm}/(2\,k^{1/2}) \qquad [5.5]$$

There is not a direct correlation between the three last equations and the non-linear Hoek and Brown criterion defined in the first equation. Consequently, determining of the values of c' and ϕ' for a rock mass that has been evaluated as a Hoek and Brown material is a difficult problem.

Having evaluated a large number of possible approaches to this problem, it has been concluded that the most practical solution is to treat the problem as an analysis of a set of full-scale triaxial strength tests. The

results of such tests are simulated by using Hoek and Brown original equation to generate a series of triaxial values. The linear relation equation, between major and minor principal stresses, is then fitted to these tests results by linear regression analysis and then values of c' and ϕ' are determined from the last two equations evaluated here (Hoek and Brown ,1997).

5.5.5.1 Determination of Hoek and Brown Parameters

The size of the sample is a very sensitive parameter to the accuracy of the test results as it has a significant influence on the rock strength, which decreases substantially with increasing sample size. Hoek and Brown (1997), have reported the results of laboratory tests on samples of 61, 101, 146 and 300 millimeter diameter of a highly cleated mid-brightness coal from the Moura mine in Australia. Table 5.3 summarizes the result of these tests involving varying size diameters.

Diameter (mm)	m_b	s	a
61	19.4	1.0	0.5
101	13.3	0.555	0.5
146	10.0	0.236	0.5
300	5.7	0.184	0.6
Mass	2.6	0.052	0.65

Table 5.3 Peak Strength of Moura Coal Mine Samples According the Sample Diameter (from Hoek and Brown, 1997).

A physical observation from La Guajira coals clearly shows the development of discrete shear surfaces with the application of a deviatoric stress, as illustrated in Figure 5.17. The bright color visible on the internal part of sample Core-3 is characteristic of the high vitrinite content of this high volatile sub-bituminous coal sample. In addition, the well developed cleat system for this sample suggests the possibility of good permeability.

5.5.5.2 La Guajira Coals

Figure 5.19 shows the regression used to determine the Hoek and Brown parameters determined for La Guajira coals and Table 5.4 lists those parameters. The parameters determined for these materials are very, similar to a coarse grain and metamorphic rock. However, it may be due to the low confining stresses used during the test that highlight the influence of dilation on the mechanical properties of the material, causing an overestimation of the frictional effects. The values of the constants compare well with the results from Hoek and Brown (1997)

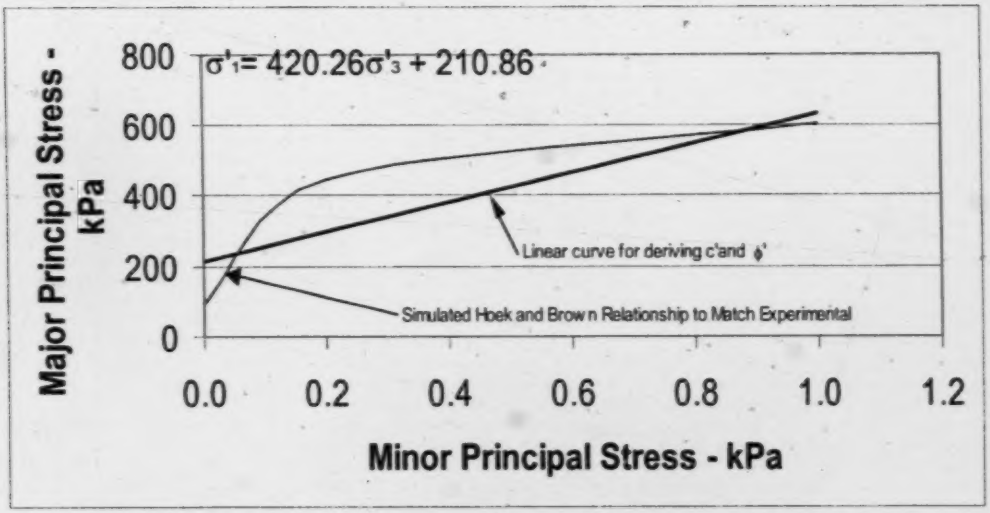

Figure 5.19 Hoek and Brown Parameters for La Guajira Field Coal.

Diameter (mm)	m_b	σ_{ci} (Mpa)	s	a
60 – 63	28.94	14.52	1.0	0.5

Table 5.4 Strength Parameters from La Guajira Field Coal.

Table 5.5 summarizes the stress-strain-strength parameters obtained for each core specimen.

Sample No.	σ'_3 (kPa)	$(\sigma'_1 - \sigma'_3)_f$ (MPa)	ε_f (%)	E (GPa)
Core – 0	0	9.6	1.7	0.91
Core – 1	200	21.1	2.0	1.32
Core – 2	400	8.9	1.9	0.62
Core – 3	1,000	24.5	2.5	1.31

Table 5. 5 Stress Results for La Guajira Field Cores

Using the computed Hoek and Brown parameters listed in Table 5.4 and the relationship defined in Equation 5.1, the shape of the failure envelope was determined and compared to the experimental, as illustrated in Figure 5.20. As shown, a reasonable agreement between the computed failure strength parameters and the results of the experimental program were obtained. Recall that the test results for sample Core-2 was significantly different from the results of the other three samples tested, suggesting a weak failure plane, and consequently was not utilized in the strength criterion determination.

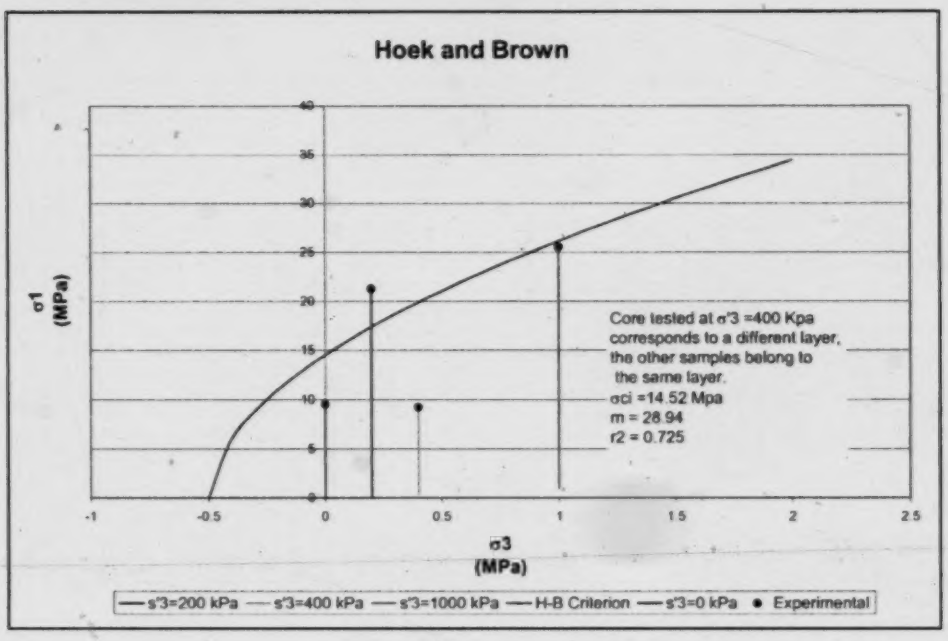

Figure 5.20 Comparison of Computed Hoek and Brown Failure Envelope with Experimental Data

5.6 BOREHOLE STABILITY CALCULATIONS TO ASSESS OPENHOLE CAVITY COMPLETION POTENTIAL IN LA GUAJIRA FIELD

The coal seams from La Guajira Field tested in the laboratory were collected from shallower seams than those of interest at the real wells. It was hoped that these shallower coals could serve as analogous materials to the coal at greater depth. Unfortunately, the extremely high strength of the coal test in this research program suggests that the possibility to create openhole cavity completions may be limited. Field experience with La Guajira 21, which was completed barefoot (i.e. no liner installed through the coal seam), demonstrated very poor wellbore stability during the initial dewatering process. Frequently, this well had to be serviced in order to clean out coal that had sloughed into the well suggesting that under typical dewatering or lowering of the fluid level in the well, sufficient stress changes occurred to fail the coal around the borehole wall.

The rock mechanical properties, m_b and σ_{ci} shown in Table 5.4, obtained from the laboratory test of shallower cores were used to compute the Mohr and Coulomb failure criterion parameters, c' and ϕ', using Equations 5.4 and 5.5. This conversion was necessary because most geotechnical software is written in terms of the Mohr and Coulomb failure criterion in which the rock mass strength is defined by the cohesion and friction angle.

Applying c' and ϕ' in a commercial geotechnical simulator, STABView®, a relation between the radius of the elastic zone affected, R, and the wellbore radius, r_w, was obtained, R/r_w. This relation was then plotted against the dynamic bottomhole pressure to assess the sensitivity of the failure to changes in bottomhole pressure. Table 5.6 provides the terms from Hoek and Brown converted into Mohr and Coulomb terms at different values of normal stress to the failure plane, σ_{nt},. The value for σ_{nt} is unknown but should be between 0 MPa and the instantaneous shut in pressure (ISIP) obtained during the hydraulic fracture work of the coal seams from wells close to La Guajira 21. Table 5.7 shows fracture data for three wells close to La Guajira- 21. The ISIP data was extracted from confidential fracturing reports prepared by BJ Services.

Hoek and Brown Terms		Mohr and Coulomb Terms		
m_b	σ_{ci} (MPa)	σ_{nt}= 0 MPa	σ_{nt}= 5 MPa	σ_{nt}= 10 MPa
28.94	14.52	c'= 67 ϕ'= 1.7	c'= 51 ϕ'= 3.2	c'= 46 ϕ'= 4.7

Table 5.6 Mohr and Coulomb Terms converted from Hoek and Brown Terms.

Well	Depth (m)	ISIP (MPa)
La Guajira 22	831.4	9.8
La Guajira 23	793.9	7.6
La Guajira 25	834.5	11.04

Table 5.7 Fracture data.

Table 5.8 shows the field data for well La Guajira-21.

Wellbore Diameter – mm	203
True Vertical Depth – m	682
Vertical Stress (Overburden) – MPa	15.4 from Density Log
Initial Formation Pressure – MPa	5.8

Table 5.8 La Guajira-21 Well data.

Using all of the above data and the laboratory computed strength parameters in the program STABView®, several analyses were conducted to examine the development of a failed region around the wellbore (i.e. a yield zone). Figure 5.21 illustrates the sensitivity of the failed zone development to normal stress, σ_n.

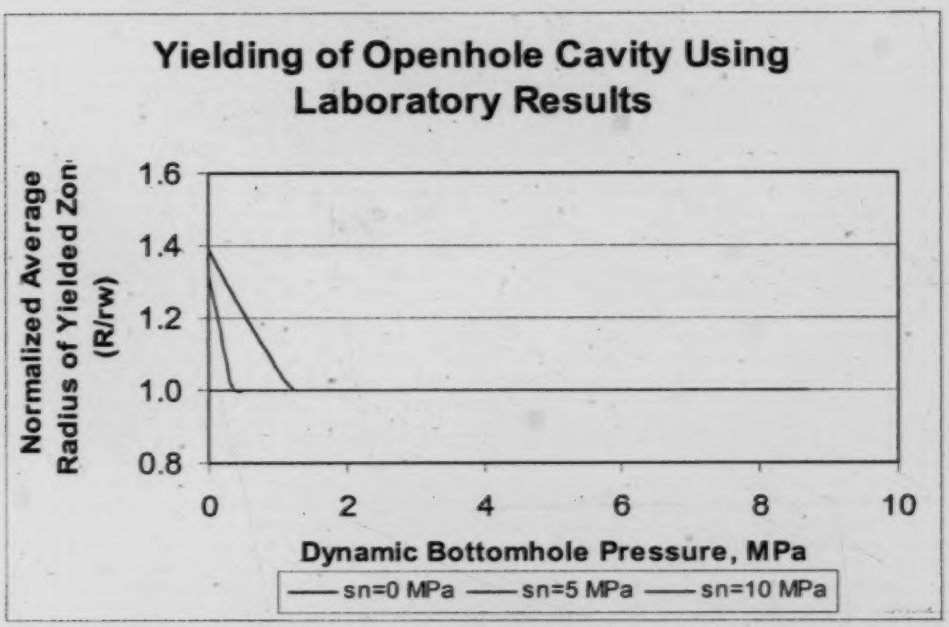

Figure 5.21 Laboratory Data Run at Different Normal Stresses Figures.

The values for the normalized average radius of yielded zone, R/r_w, shown in Figure 5.21 indicate that in the best case, the largest cavity that could be created in this case would be around 1.4 times the radius of the wellbore, and would only happen when the dynamic bottomhole pressure was reduced to 0 MPa.

To examine the range of possible coal strength properties that may have existed in well La Guajira 21, where sloughing of the openhole section had occurred, the analyses were repeated using varying strength properties. Again using STABView® and knowing that a cohesion value for soft, cleated coal is 0.1 and for a strong and brittle coal is 2, two extreme type of coals, simulations were run to explore the possibility for creating openhole cavity completion into deeper coal seams. The sensitivity parameters adjusted for the simulation were cohesion and friction angle. Table 5.9 shows the range of c' and ϕ' used in the simulation.

Cohesion (MPa)	0.1	1.0	2.0
Friction Angle (Deg)	20	30	40

Table 5.9 Sensitivity Parameters for STABView® Analyses

Figures 5.22, 5.23 and 5.24 illustrate the simulations results for cohesion values of 0.1, 1.0 and 2.0 MPa, respectively. Each value of cohesion was evaluated considering all three friction angles.

For a low cohesion value of 0.1 MPa, as illustrated in Figure 5.22, the zone of failure or the size of the zone created during any openhole cavity completion process is computed to be between 11 and 18 times r_w as a result of decreasing the bottomhole pressure. While the value of R/r_w looks relatively small for successful cavity completions, it provides direction on the magnitude of pressure changes required for the downhole and at the surface.

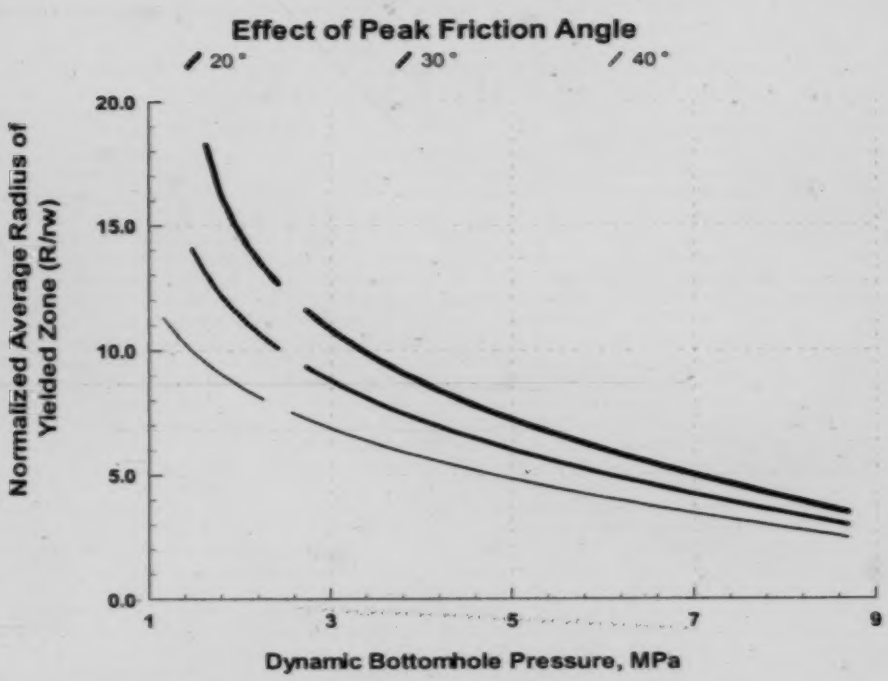

Figure 5.22 Simulation Results with a cohesion of 0.1 MPa.

Figure 5.23 shows the results of the simulation for a coal with a cohesion of 1.0 MPa. In this case, the R/r_w is slightly lower than for c'=0.1 MPa but still seems to indicate that there is the possibility to create openhole cavity in this kind of coal seam.

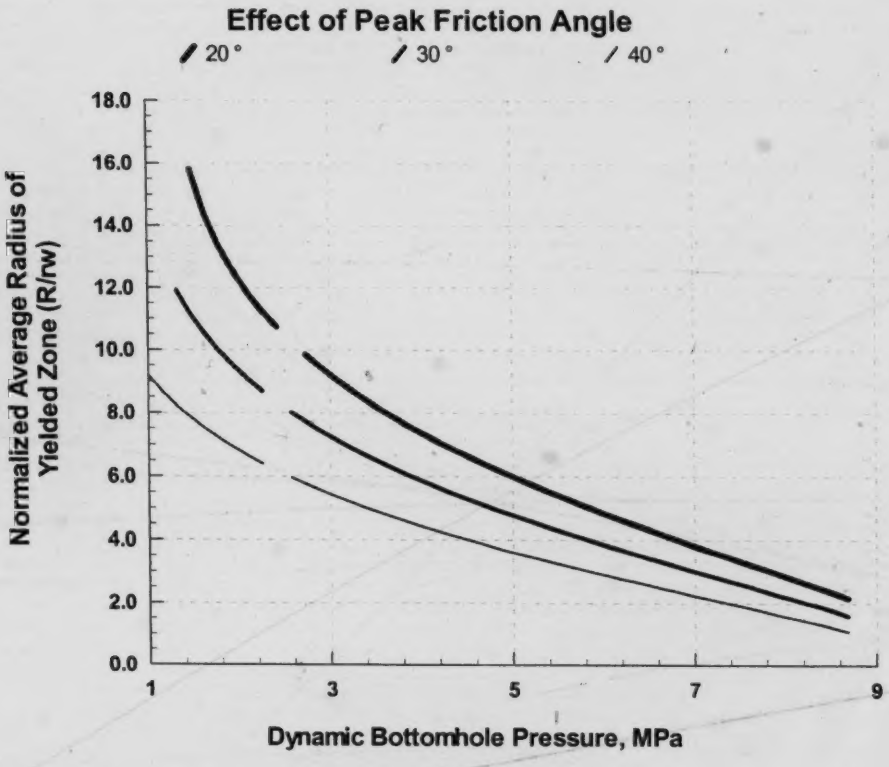

Figure 5.23 Simulation Results with a cohesion of 1.0 MPa.

For a cohesion of 2.0 MPa, Figure 5.24 illustrates the range of yield zone development for each value of friction angle. Even of the higher value of cohesion, there still appears to exist the possibility that failure will occur around the borehole wall under conditions of low bottomhole pressure.

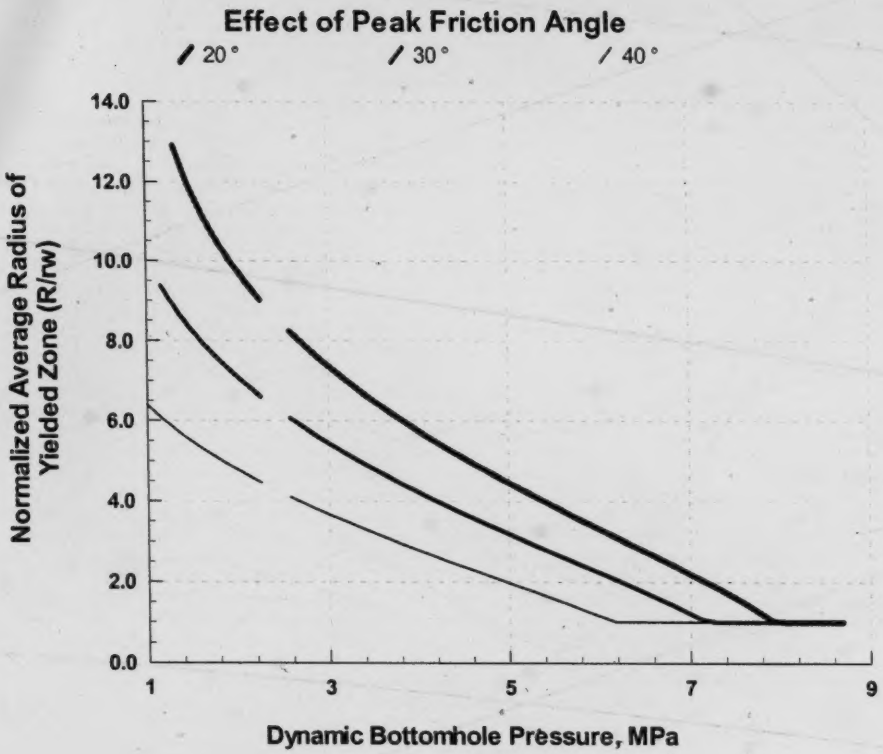

Figure 5.24 Simulation Results with a cohesion of 2.0 MPa

5.7 SUMMARY

The simulation results have demonstrated that the in situ properties of the coal in La Guajira – 21 are substantially different than the properties obtained from the laboratory tests on shallow mine coal specimens. Field behavior of La Guajira – 21 showed that borehole instability or the development of failed zones occurred on a regular basis. The STABView results support this phenomena only for low strength values of the coal. If the strength values of the coal is modeled using the lab test results, the

potential for yield zone development is almost negligible. While the laboratory tests provide valuable information on the properties of Colombian coal, they likely do not represent in situ properties. Consequently, further assessments of the potential for openhole cavity completions in the La Guajira field will require testing of the in situ reservoir coal.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

6.1.1 Specimen Considerations

The cores utilized in the testing program were collected from a mine site and kept in a refrigerator for a period of one year at a temperature lower than –10°C. Due to the long storage period, it is very probable that the mechanical rock properties of the samples may have suffered some alteration to a degree that could affect the final results. It is suggested that experimental programs on this core be conducted as soon as possible after coring.

For the research conducted in this thesis, it was impossible to use samples directly from the coalbed methane wells described in chapter 4. Cores from a local mine, but from shallower seams and subject to less pressure and temperature effects were obtained for the testing program. It was hoped that the properties obtained from these coal specimens would serve as a suitable analog for the in situ coal. While these specimens provided useful information on the stress-strain-strength characteristics of Colombian coal, borehole stability calculations for the in situ conditions of a well which experienced yielding and repeated sloughing of the coal into the wells showed that the shallow wall properties substantially over predict the strength of the reservoir coal seams.

6.1.2 Practical Application of the Laboratory Work

Prior to any operational work in the field to create a cavity in any prospective well for coalbed methane production, it is highly important to determine the rock mechanical properties in order to estimate the level of success of the openhole cavity completion technique application.

In this particular work, the results obtained from the laboratory test and some hydraulic fracturing information were used to run a borehole stability simulator in order to evaluate the possibility to create a cavity in the wells from La Guajira field. The answers obtained from the simulator were encouraging, using a range of values most likely applicable to La Guajira Field's coal (cohesion factor from 0.1 to 2.0 MPa and a friction angle from 20 to 40 degrees), indicating that it may be possible to create an openhole cavity completion ranging from 6 to 18 times the borehole diameter. This effect would be reached only by decreasing the dynamic hydrostatic pressure of the well. One possibility is to apply artificial pressure from surface, by injecting a mixture of water and air for example, and then abruptly releasing the total pressure to achieve a cavitation diameter that could be considered to be optimal.

The results obtained from laboratory tests will help to plan the operations work, and provide costs saving, in terms of equipment, for the exploitation of a coalbed methane reservoir.

6.2 RECOMMENDATIONS

6.2.1 Samples and Tests

It is highly recommended to drill a new well in the prospective area and obtain representative coal seam samples from the productive interval being evaluated. In this way, test results will be applicable to the pay zone intervals of interest directly instead of the simulated information. It is also important to properly conserve, protect and store the samples in order to avoid changing their rock mechanical properties. Then, a complete set of triaxial tests including permeability evaluation should be performed.

6.2.2 Technique Applicability and Future

Since the openhole cavity completion stimulation technique much cheaper than hydraulic fracturing and the production results possible being far more promising, it is strongly recommended to gain additional knowledge of the geology, completion methods and rock mechanical properties of the exploration region. The exploration area is huge and the quality of the coal seams optimum for coalbed methane exploration in the northern part of Colombia. This information is therefore required to develop this vast resource and produce, perhaps, one of the biggest coalbed methane reservoirs in Latin America. The future of a reservoir of this calibre, which could take as much as two decades in the primary recovery stage, would produce energy for the area, prosperity and wealth for the community and the project investors.

REFERENCES

Bachu S.: "Hydrogeological and Stress Regimes in the Cretaceous Coal – Bearing Strata of Alberta". Third Annual Coalbed Methane Conference, pp. 451 - 482, Calgary, October 2001.

Bowles J.: "Engineering properties of Soils and Their Measurement" Four Edition, McGraw-Hill Inc., pp. 43 – 88,1992.

Buck K. and Ruhl S.: "Helper Field: A Multidisciplinary Approach to CBM Development – Unita Basin, Utah". Third Annual Coalbed Methane Conference, pp. 17 – 79, Calgary, October 2001.

Fadness D.; Exploration and Production Methods – Powder River Basin". Third Annual Coalbed Methane Conference, pp. 105 – 127, Calgary, October 2001.

Fraser J.: "Global CBM Opportunities: Applying the Experience of the San Juan Basin". Third Annual Coalbed and Coal Mine Methane Conference, pp. 203 – 208, Denver, March 2002.

Garrat R. F. J.: "Extracting and Utilizing CBM/CMM in the UK". Third Annual Coalbed and Coal Mine Methane Conference, pp. 39 – 47, Denver, March 2002.

Gotkas B, and Ertekin T.: "A comparative Analysis of the Production Characteristics of Cavity Completions and Hydraulic Fractures in Coalbed Methane Reservoirs". SPE Paper No. 55600, pp. 131 – 140, 1999.

Haynes D. C.: "Appraising CBM resources in Active Mining Areas". Third Annual Coalbed and Coal Mine Methane Conference, pp. 459 – 468, Denver, March 2002.

Hill D.: "Completion Approach for Frontier CBM gas Plays". Third Annual Coalbed Methane Conference, pp. 43 – 72, Calgary, October 2001a.

Hill D.: "Gas Storage Characteristic of Fractured Shale Reservoirs". Third Annual Coalbed Methane Conference, pp. 176 – 185, Calgary, October 2001b.

Hoek E., and Brown E. T.: "Practical Estimates of Rock Mass Strength". Int. J. Rock Mech. Min. Sci. Vol. 34 No.8, pp. 1165 – 1186. 1997.

Kozera G. and Weida D.: "CBM Project Evaluation and Case History". Third Annual Coalbed and Coal Mine Methane Conference, pp. 52 – 77, Denver, March 2002.

Langmuir I.: "The Constitution and Fundamental Properties of Solids and Liquids ". Journal of American Chemical Society, pp. 221 – 232, 1916.

Levine, R. J: "Model Study of the Influence of Matrix Shrinkage on Absolute Permeability Of Coalbed Reservoir". Coalbed Methane and Coal Geology, Geological Society Special Publication, No. 109 pp. 197 –212, 1996.

Logan T. L., Clark W. F., and McBane R.A.: "Comparing Cavity and Cased Hole Hydraulic Fracture Completion Techniques, San Juan Basin, New Mexico". SPE Paper No. 19010, pp. 1 – 43, 1999.

Logan T.L., Mavor M.J., and Khordaverdian M.: "Optimaztion and Evaluation of Open Hole Cavity Completion Techniques for Coal Gas Wells". SPE Paper No. 25859, 1 – 32, 1993.

McCants C.Y and Spafford S.: "Five Spot Pilot On tight Spacing: Rapid Evaluation of CBM Block in the Upper Silesian Coal Basin, Poland". Third Annual Coalbed Methane Conference, pp. 245 – 287, Calgary, October 2001.

Palmer I., Vaziri H., Mclennan J., Prasad K.V., Kutas M., and Fincher R.: "Completions and Stimulations for Coalbed Methane Wells". SPE Paper No. 30012, pp. 501 – 516, 1995.

Scott A.: "A CBM Producibility and Exploration Model: Defining Exploration Fairways". The 2001 International Coalbed Methane Symposium, The University of Alabama, pp. 12 – 67, Tuscaloosa, May 2001b.

Scott A.: "Application of a Coalbed Methane Exploration Model for Developing CBM Resources in Canada". Third Annual Coalbed Methane Conference, pp. 117 – 146, Calgary, October 2001a.

Young G.B.C., Kelso B.S., and Paul G.W.: "Understanding Cavity Well Performance". SPE Paper No 28579, pp. 373 – 381, 1994.

APPENDIX A TRIAXIAL CELL CALIBRATION CHARTS

This appendix contains the results obtained during the calibration process for each sensor used in the Triaxial cell.

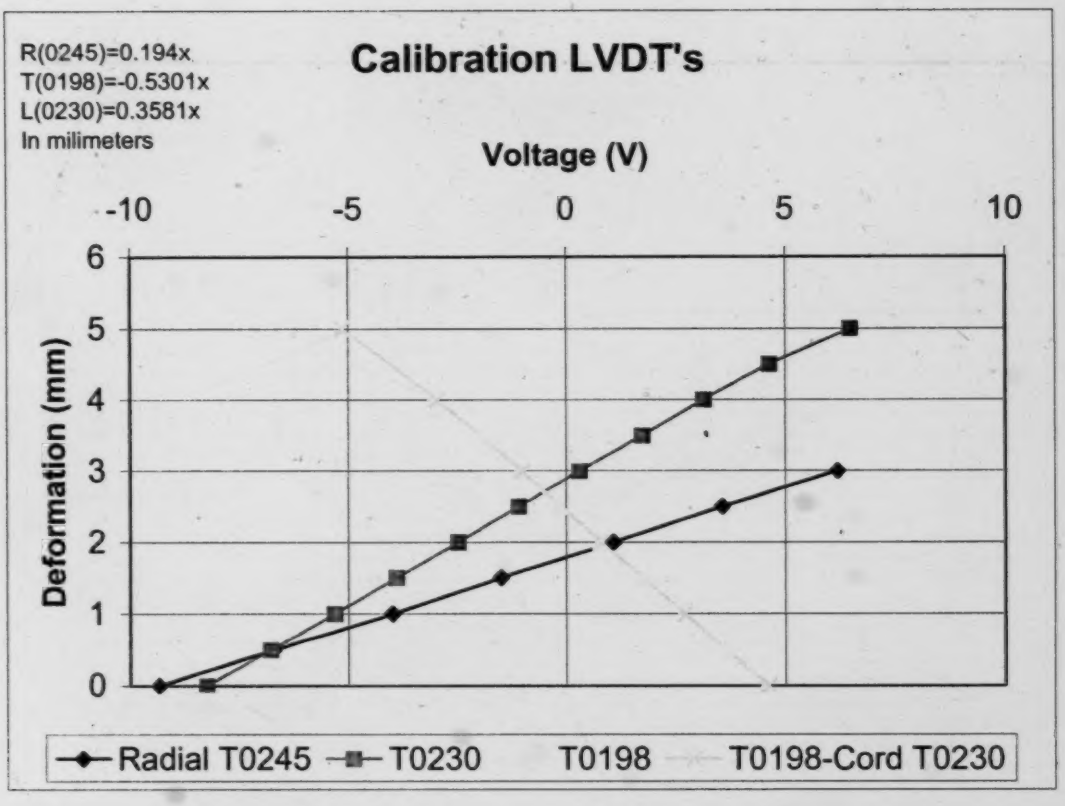

Figure A-1 Cell-1 Strain Sensor Calibration data, LVDT (Linear Voltage Deformation Transducer)

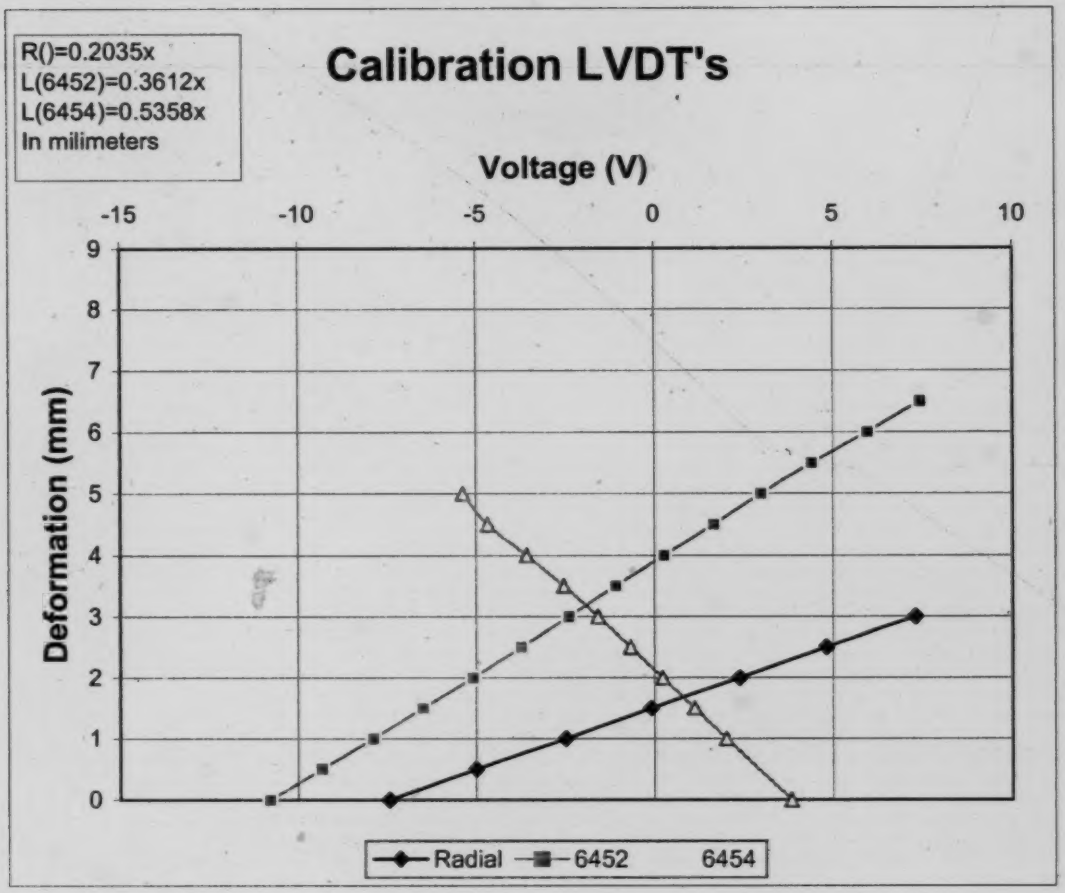

Figure A-2 Cell-2 Strain Sensor Calibration data, LVDT (Linear Voltage Deformation Transducer)

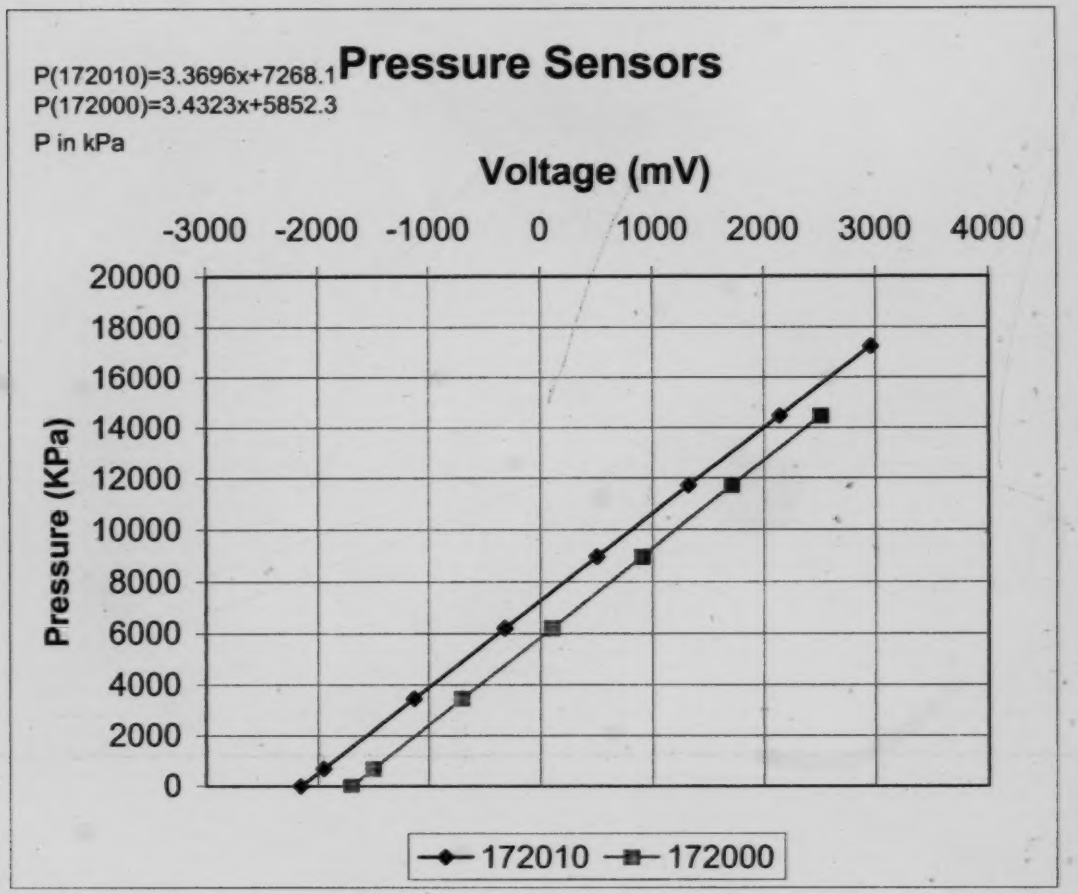

Figure A-3 Pore Pressure Sensor Calibration data

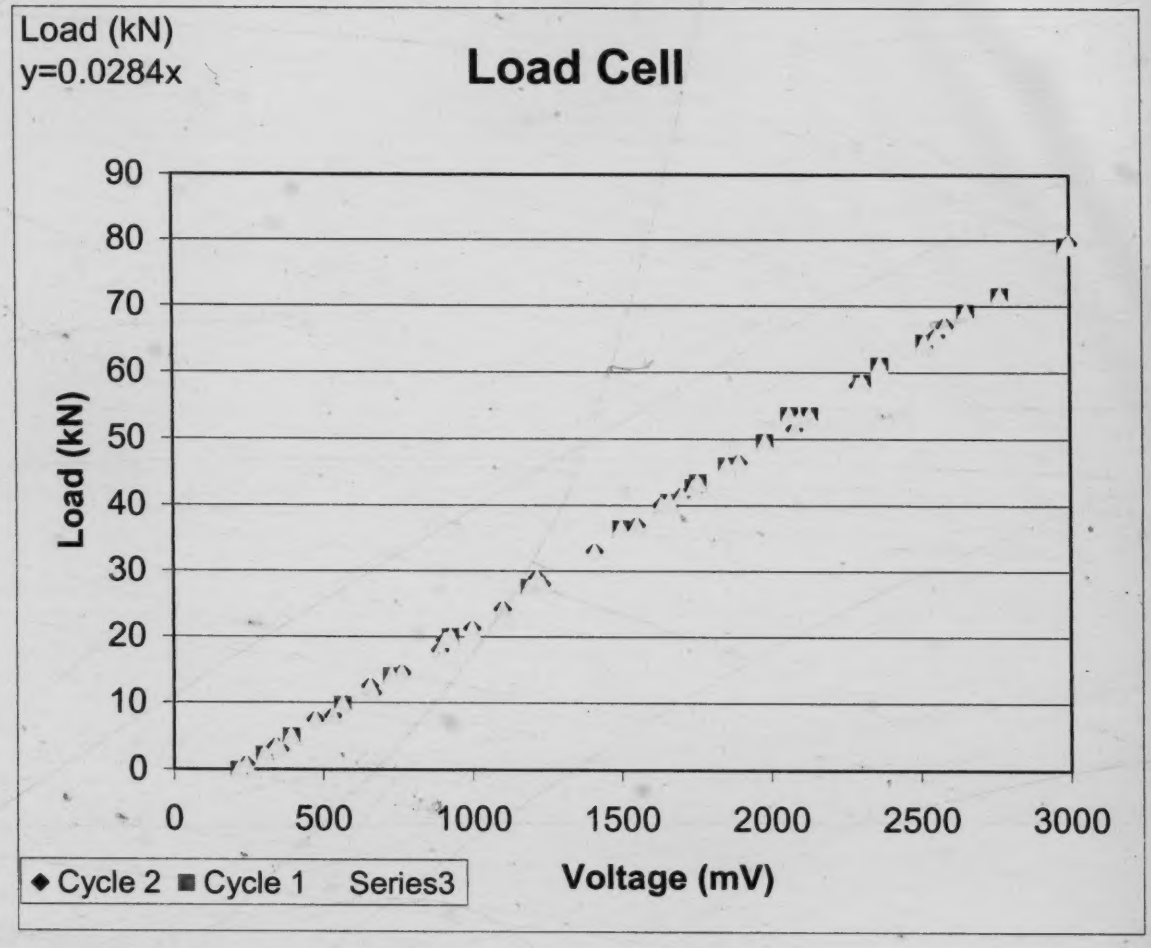

Figure A-4 Load Cell Sensor Calibration data

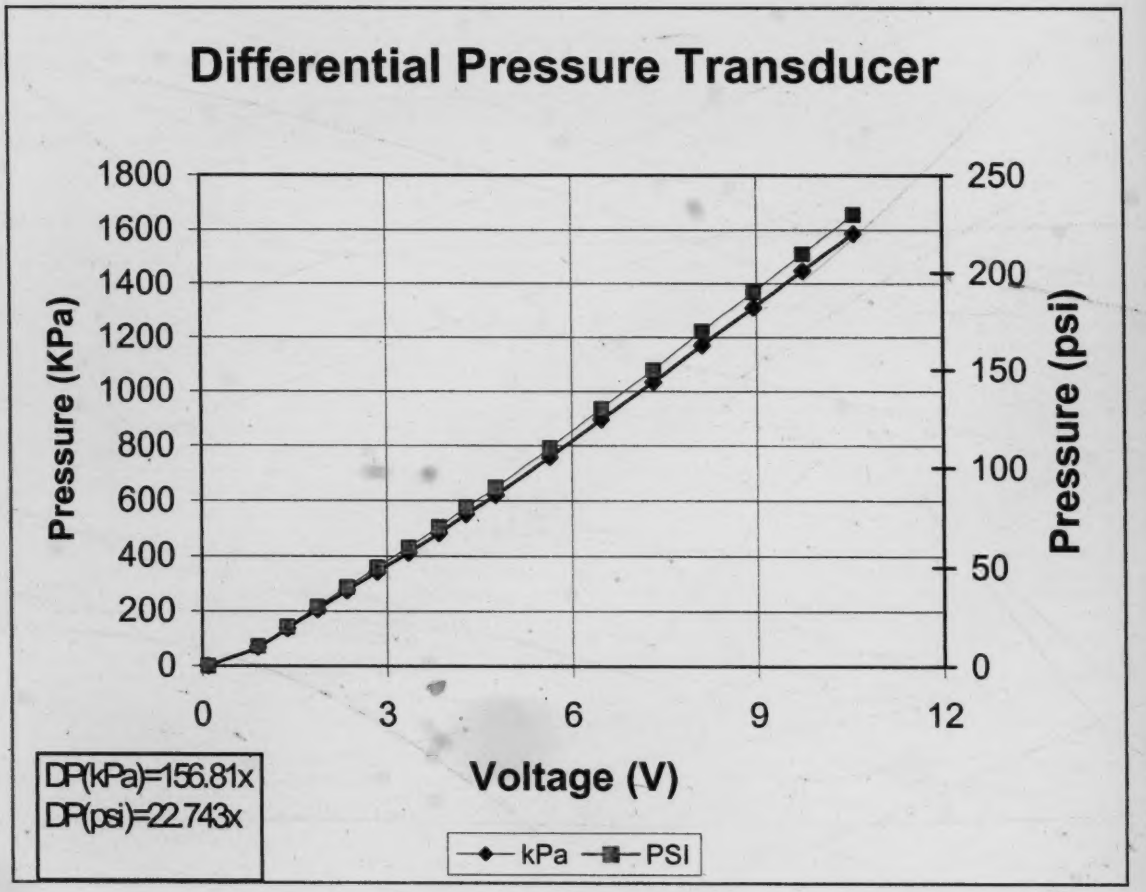

Figure A-5 Differential Pressure Transducer Sensor Calibration data

APPENDIX B OPERATION HISTORY IN LA GUAJIRA FIELD

This appendix contains detail sequential information done in each well of La Guajira Field.

B.1 Well Guajira - 21

Well Guajira - 21 was spudded in February 1996 and reached a total depth of 920 m, Figure B.1 shows the final configuration of the well, including coal seams intervals and amount of sand admitted per coal seam during fracturing jobs. Mechanical hole problems prevented the well from being logged below 746 m. Using log, drilling, and correlation data form the CH-2 core hole, it was empirically determined that approximately 120 m of coal pay were present in the hole. Three hundred twenty nine feet were read directly from the open hole log. A coal seam from 690 m to 695 m, containing 5 net m of coal, was chosen as the primary objective for completion. The cavity completion method was chosen because of its success when used on similar coals in the San Juan basin. It also offered the potential for substantial cost saving over a conventional hydraulic fracture job. Five and one half inch casing was set at 672 m and the well was cavity completed. Well Guajira - 21 was put on production in early September 1996 and produced until late October 1998. Water production stabilized at 15 to 20 barrels per day (BPD) while gas production never rose above 10 thousand cubic feet per day (MFD). Based on these results, the cavitation completion was deemed ineffective and it was decided to fracture coal seams selected in the interval 690 m to 695 m.

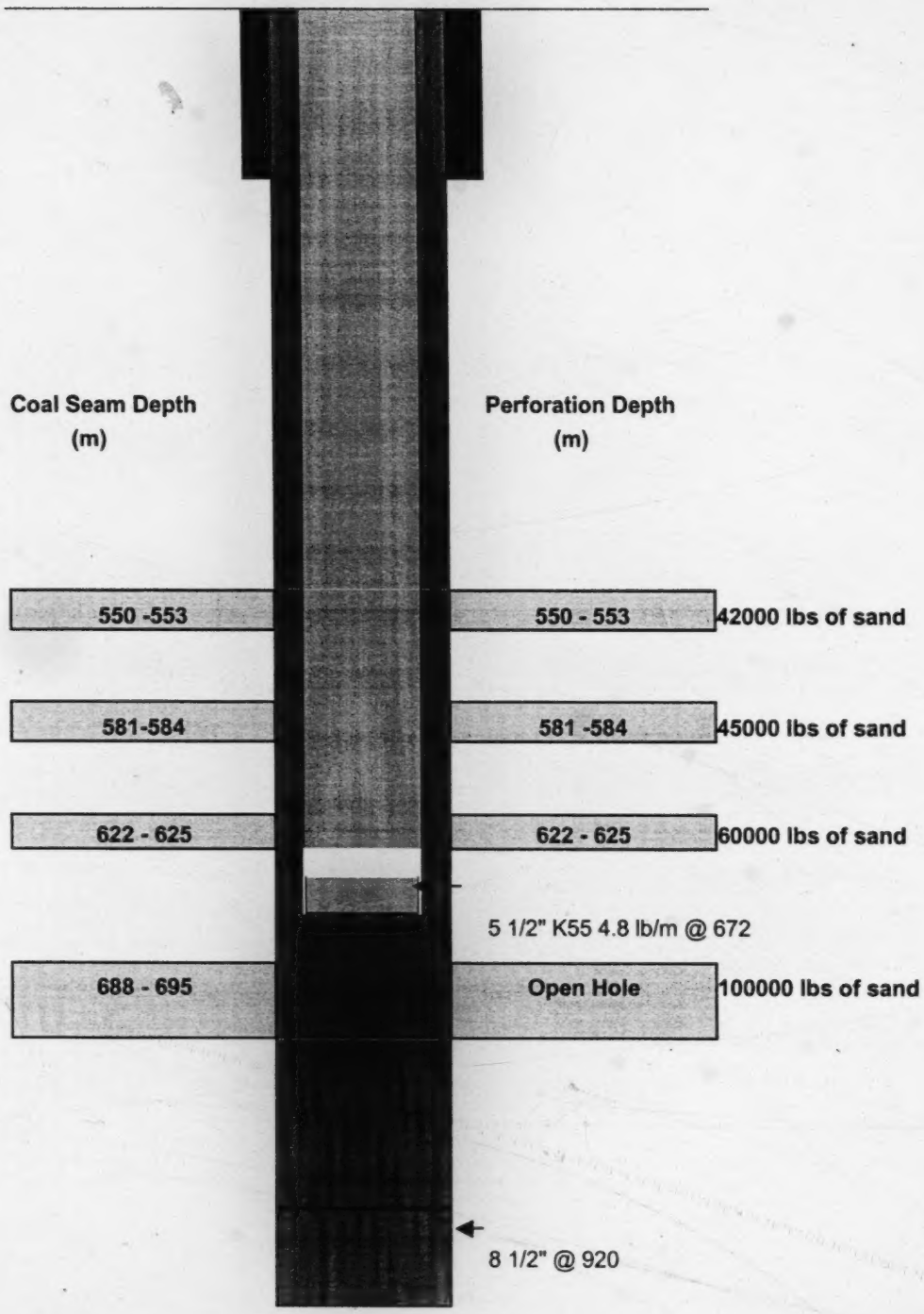

Figure B.1 Well Schematic "Guajira - 21".

During the fracture jobs, some coal seams did not admitted the total amount of sand planned initially, this is the case for the intervals 582 m to 585 m and 550 m to 554 m where the fracture job were stopped prematurely, with less than 50% of the sand designed to be pumped.

B.2 Well Guajira - 22

Well Guajira - 22 was spudded in November 1997 and reached a total depth of 901 m. Net total coal thickness of over 105 m was measured from the open hole log. This well was cased to a depth of 895 m. Coal seams from 834 m to 570 m were targeted for completion, as is shown in Figure B.2.

In April 1998, the coal interval at 831 to 834 m was fractured. The job was pumped as planned, with an instantaneous shut in pressure (ISIP) of 1425 psi. The fracture gradient was calculated at 0.3 psi/m. The total programmed sand was injected into the coal seam interval.

The other attempts to stimulate the coal seams were not successful due to the early increase of both downhole and surface pressures when the sand reached the formation. Evaluating the pressure performance during the stimulation jobs and the operation events, some assumption can be made to explain the fracture failure in those intervals: perforation problems,

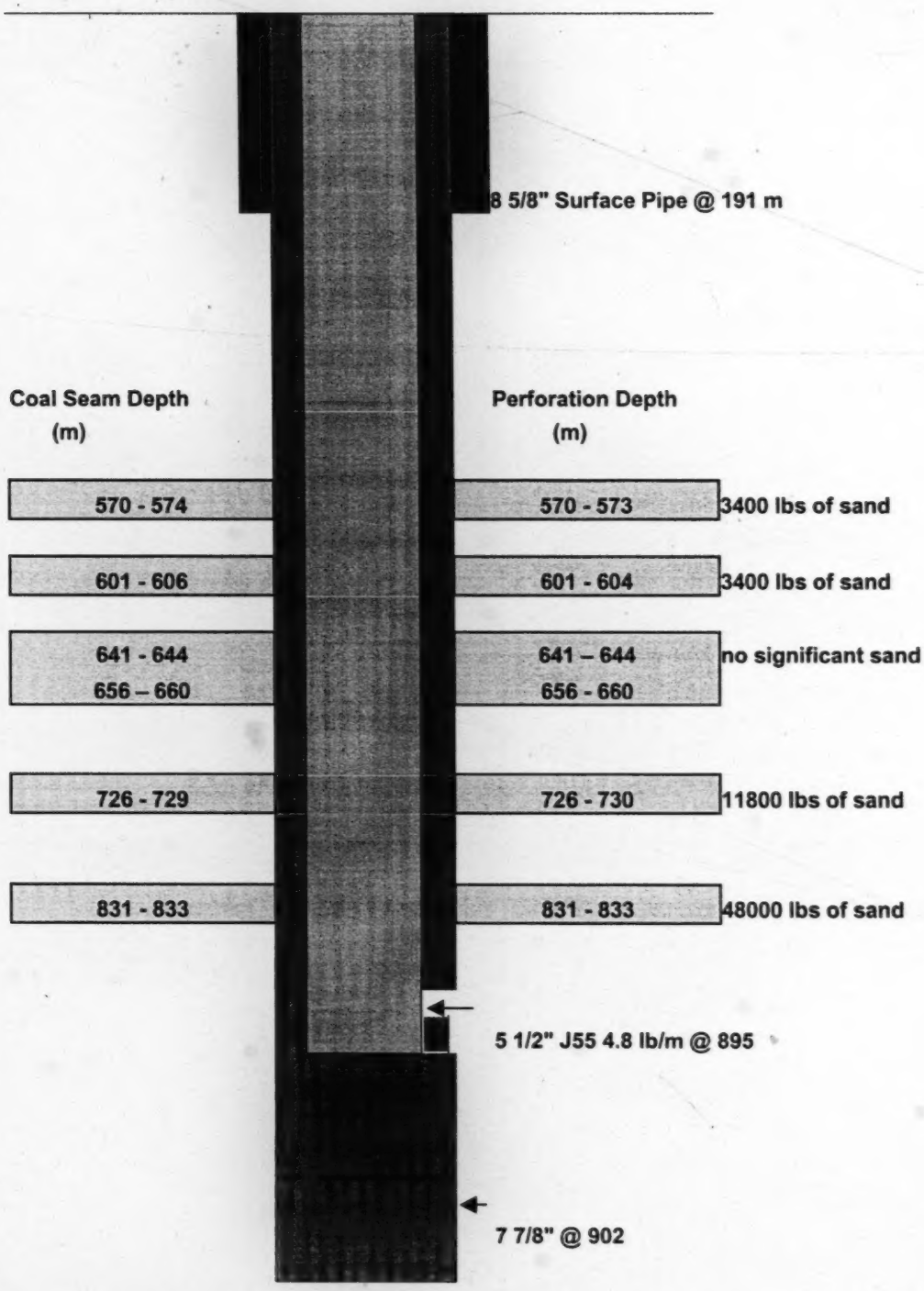

Figure B.2 Well Schematic "Guajira - 22".

tortuosity, the initiation of multiple fractures or high lateral stresses in the coal seams.

Perforation problems were discounted because of the lack of effect by the acid during perforation clean up and by the pressure response after the screenout. Additionally, after each perforation run, the gun was checked to ensure that all shots fired. It is believed that the initiation of multiple fractures was the primary problem, but the other possibilities cannot be excluded.

Clean out of the well Guajira - 22 began in May 1998. The fracture plugs were drilled and sand was circulated out down to a depth of 869 m, providing over 31 m of "rat hole" below the lowest completed interval. The well was completed and ready to initiate production test.

B.3 Well Guajira - 23

Well Guajira - 23 was spudded in June 1998. The total depth of the well was at 801 m. Over 111 m of coal were measured from the electrical logs. Five and one half inch production casing was set at 800 m and then cemented, as is shown in Figure B.3.

A single interval containing multiple coal seams was chosen for completion. Four net m of coal were present in the depth interval of 776 to 794 m.

Based on past experience, changes were made in the fracture design. The 10-barrel, 28% HCl acid perforation breakdown/clean up treatment was left unchanged, as well as the 30% of total volume pad stage. Changes were made in the early sand stages. Low concentration sand stages were added to the beginning of the job in order to plug possible sources of leak off and gauge the pressure response to small concentrations of sand. The low concentration sand stages functionally increased the pad size. Also, total design sand was increased to 2462 pounds per m.

The fracture job were done in November 1998. The stimulation job was terminated normally and an ISIP of 1025 psi was read and a fracture gradient of 0.25 psi/m calculated.

In November 1998, clean out operations began and the wellbore was circulated clean to 800 m. The well was completed as planned and surface facilities were installed.

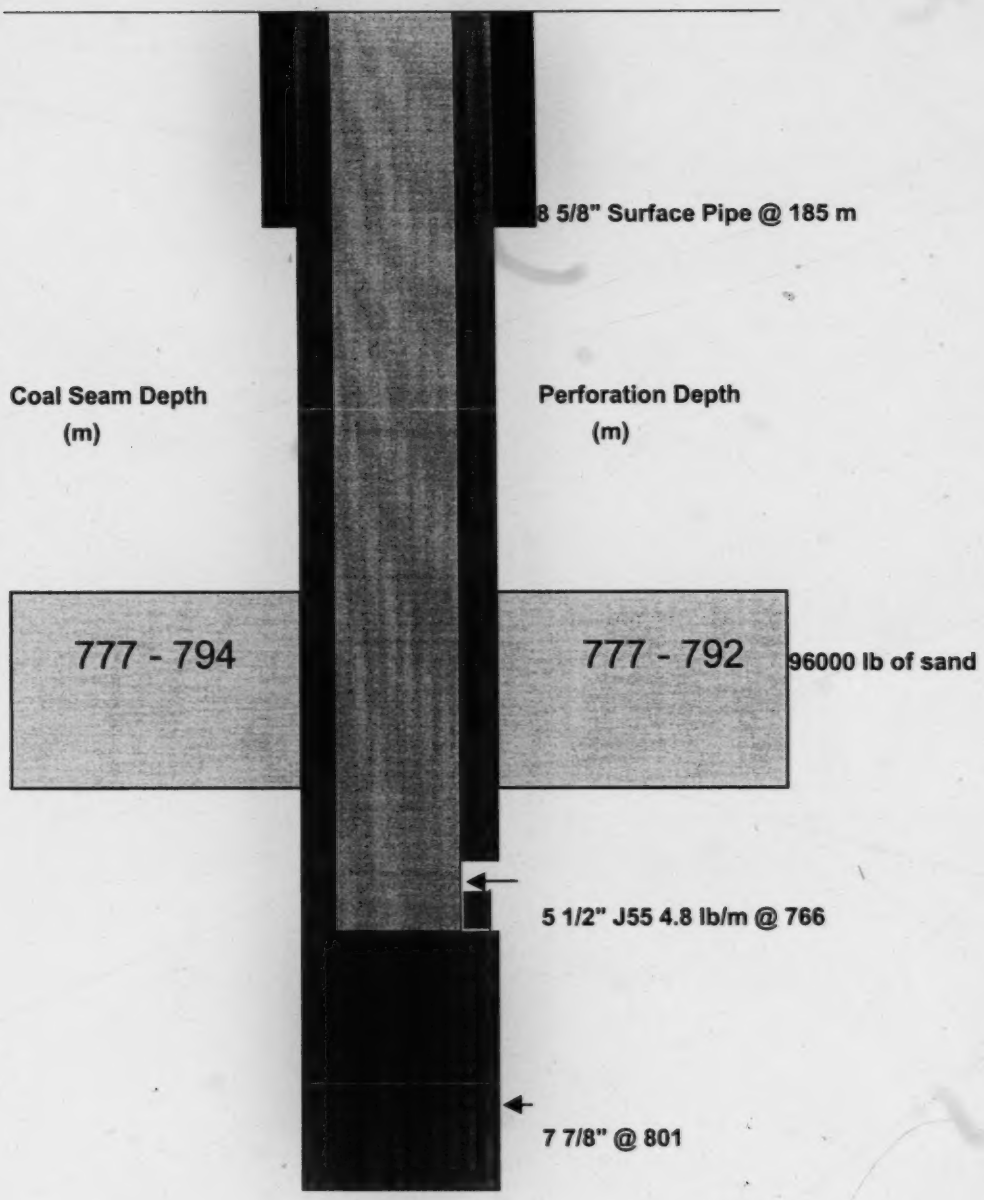

Figure B.3 Well Schematic "Guajira - 23".

B.4 Well Guajira - 24

Well Guajira - 24 was spudded on January 24, 1998. Drilling progress was excellent until January 31. The mud pump engine failed due to water in the fuel. When the pump was made operational again, the drill string was stuck in the hole at 700 m. Circulation was possible, but the pipe would not move up or down. Several methods were used to try and free the stuck drill pipe. Free - point / back-off equipment was called in, and the free-point was located at +/- 307 m. The pipe was backed off at 305 m, and a set of jars was run, but the pipe did not work free. The hole was then temporarily abandoned.

When the rig was moved back to resume fishing, additional coal had heaved into the wellbore, filling it to 271 m. Continued fishing operations were considered too risky, and a gamma ray was run from 305 m to surface. A substantial coal seam at 264 to 295 m was identified as a good candidate to test the productivity of the shallow seams in the area. Casing was run to 303 m and cemented as previously specified. A gamma ray/cement bond log/collar locator was run showing good bond through the targeted coal seam and top of cement at 92 m.

In May 1998, completion operations began on the well. The coal seam interval, targeted from 264 to 273 m, was fractured, and a total of 70,149 pounds of sand were pumped.

The sand was cleaned out to a depth of 278 m when the tubing became stuck in the hole. While attempting to work the tubing free, it parted at 85 m. The well was once again temporarily abandoned. In January 1999, fishing operations begun. The stuck pipe was freed on February 6, and pulled out of the hole. The remaining sand was then washed out of the hole to a depth of 300 m. The tubing, rods, and pump were then run, seating the pump at 256 m. Work was then commenced installing the surface facilities. Figure B.4 shows the actual well schematic.

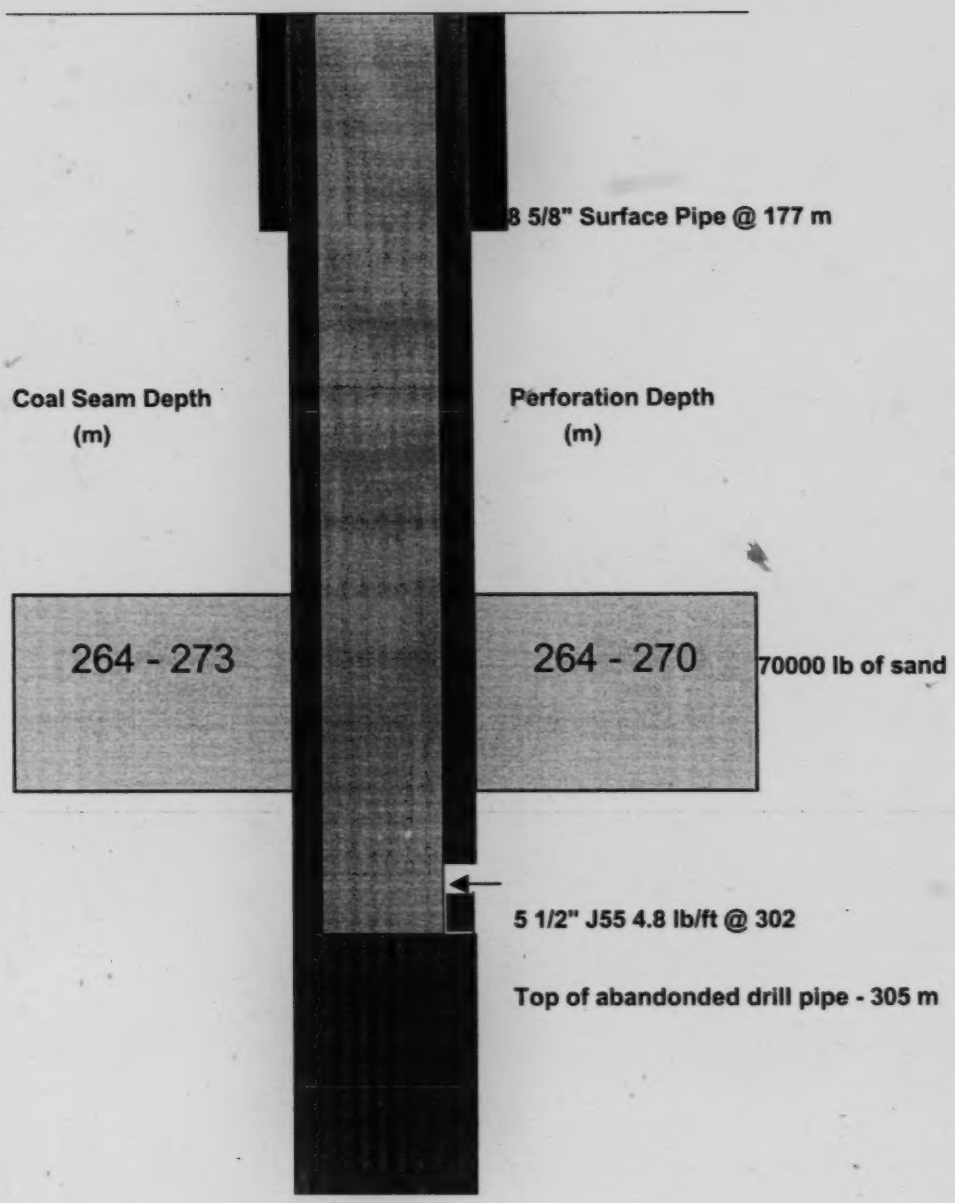

Figure B.4 Well Schematic "Guajira - 24".

B.5 Well Guajira - 25

Well Guajira - 25 was spudded in December 1997 and reached a total depth of 915 m. Over 108 net meters of coal were measured from the gamma ray/compensated density logs. Casing was run to 906 m and cemented. Seven intervals were targeted for completion from 868 to 531 m. Figure B.5 shows the coal seams stimulated and the amount of sand pumped in each interval.

This well was stimulated successfully in the two deepest coal seam intervals only. The rest of the intervals reached a success estimated at 20 to 35% of the job initially planned. The ISIP measured in the interval 827 to 835 m was 1705 psi, and the fracture gradient was 0.32 psi/m.

The above effect is quite similar to that one that happened at the well Guajira - 22, where the deepest interval was the only one fractured with success.

In mid-July 1998, the fracture plugs were drilled and the sand was washed out down to 902 m. Tubing was run with the seating nipple set at 737 m. The 2-inch external diameter of the down hole pump was run on the 7/8 inch rod string and landed in the seating nipple. The beam pumping unit was then moved onto location, set, and connected to the polished rod. Water lines, gas lines, and orifice flanges were then installed.

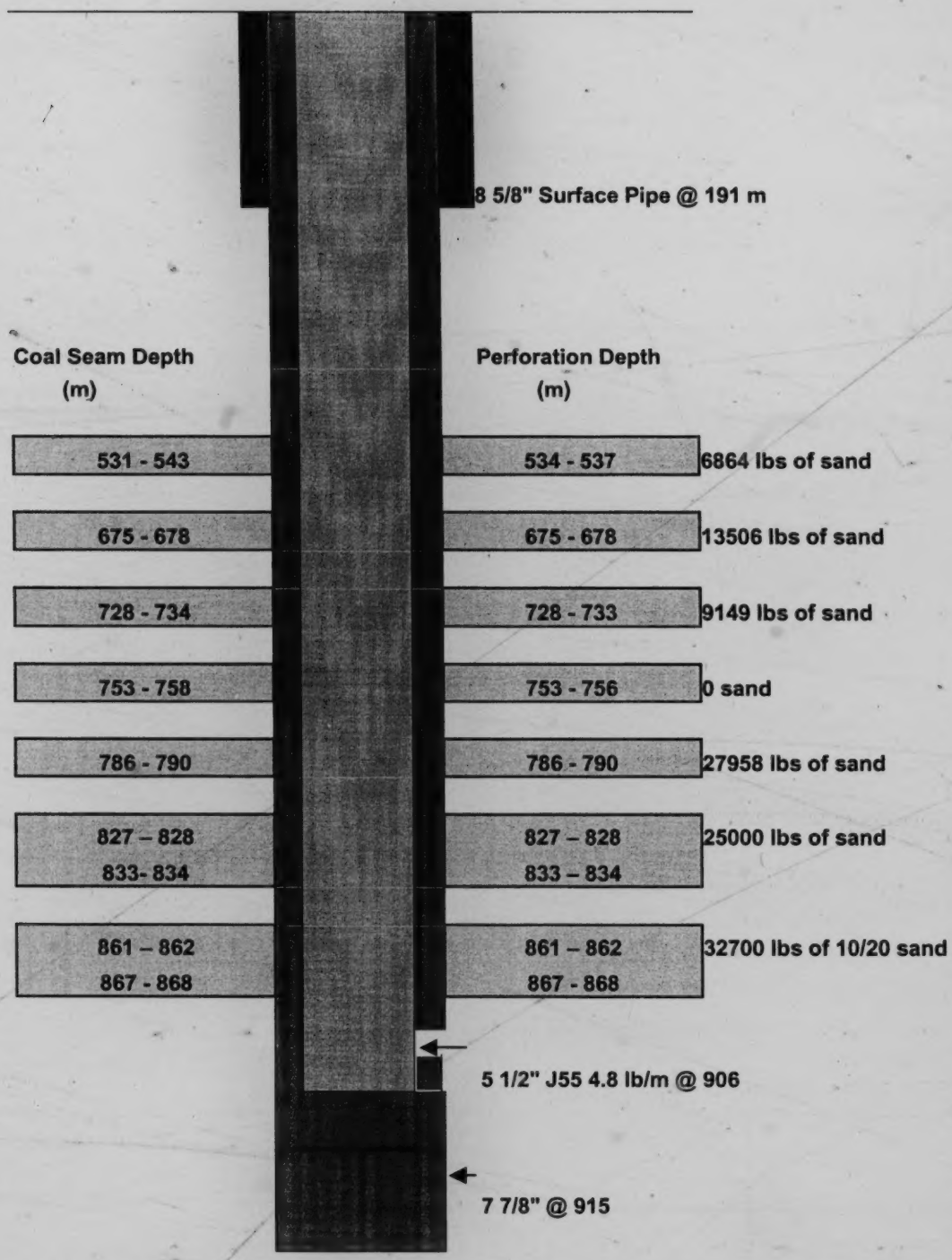

Figure B.5 Well Schematic "Guajira - 25".